İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

HYDRODYNAMIC SIMULATION OF THE BOSPHORUS

M.Sc. Thesis by

Civil Eng. Onur AKAY

Department : **Civil Engineering**

Programme: **Hydraulics Engineering**

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<u>İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY</u>

İSTANBUL BOĞAZI’NIN HİDRODİNAMİK SİMULASYONU

Yüksek Lisans Tezi

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PREFACE

The Strait of Istanbul (SOI), named The Bosphorus, constitutes a passageway between European and Asian continents and has always been an attractive place for the people due to its natural beauty. In addition to this, it has also been drawing the engineers’ attention on its stratified two-way flow since centuries.

In this study, it is intended to generate a three-dimensional computer model simulating the hydrodynamics of the Bosphorus flow, using moderate current conditions of the region. It is a great pleasure for me to carry out this kind of work that has been actually forcing, influential and interesting.

I would like to thank to the Department of Navigation, Hydrography and Oceanography of the Turkish Navy (DNHO) for supplying the bathymetry maps of the northern Marmara Sea including The Bosphorus Strait in the enclosure of the TUBITAK project (GIS for a coastal zone under threaten of an earthquake) that has been carrying out by our department.

I am thankful to Allen COOPER and Michael TURNBULL for their valuable contributions during my study at HR Wallingford, England and special thanks to John BAUGH for his supports on behalf of our working group of TUBITAK project.

I would like to give my gratitude to my supervisor Prof. Dr. Sedat KABDAŞLI for his supports and advices. I would like to thank to research assistants Dilek Eren MERCAN and Oral YAĞCI for their motivation and courage they have given me since starting of my master of science at this department.

I would also like to thank to my family for their endless supports on my whole studies.

May 2002 Onur AKAY

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ABBREVIATIONS

SOI	: Strait of Istanbul
AMP	: Advanced Microstructure Profiler
ADCP	: Acoustic Doppler Current Profiler
DEM	: Digital Terrain Model
SAR	: Synthetic Aperture Radar
GPS	: Global Positioning System
DNHO	: Department of Navigation, Hydrography and Oceanography of the Turkish Navy
Ppt	: Parts Per Thousand
UNESCO	: United Nations Educational, Scientific, and Cultural Organization
SWATH	: Small Waterplane Area Twin Hull
R/V	: Research Vessel
LNH	: Laboratoire National d'Hydraulique
EDF	: Electricité de France
CTD	: Conductivity-Temperature-Depth

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R	: Rossby radius of deformation
f	: Coriolis parameter
h	: Water depth
g	: Accelaration due to gravity
$\mathbf{F_K}$	: Densimetric Froude number
$\rho_{\mathbf{K}}$	: Density
$\mathbf{G^2}$	: Composite Froude number
u	: Water velocity component in x direction
v	: Water velocity component in y direction
w	: Water velocity component in z direction
S	: Sea bed elevation
T	: Active or passive tracer
p	: Pressure
$\nu_{\mathbf{H}}, \nu_{\mathbf{Z}}$	: Velocity diffusion coefficients
$\nu_{\mathbf{HT}}, \nu_{\mathbf{ZT}}$	: Tracer diffusion coefficients
$Z_{\mathbf{f}}$	: Bottom elevation
$\Delta\rho$	: Variation in density
t	: Time
x, y, z	: Space components
Fx	: Source term in x direction
Fy	: Source term in y direction
Q	: Tracer source or sink
ω	: Angular velocity of the earth
$a_{\mathbf{vent}}$	: Wind resistance coefficient
$U_{\mathbf{vent}}$	: Wind velocity component in x direction
$V_{\mathbf{vent}}$	: Wind velocity component in y direction
P	: Precipitation
R	: Runoff
E	: Evaporation
Qb	: Net outflow

İSTANBUL BOĞAZI’NIN HİDRODİNAMİK SİMULASYONU

ÖZET

Bu çalışmada, İstanbul Boğazı’nın hidrodinamik özellikleri üç boyutlu bilgisayar yazılımı olan TELEMAC-3D kullanılarak modellenmiştir. Hidrodinamik özellikler üç boyutlu Navier-Stokes denklemleri kullanılarak çözülmüş ve bu temel denklemlerin yanısıra kullanılan parametrelerin ve sınır koşulların açıklaması da bu çalışmada yapılmıştır. Ayrıca bu çalışmada, TELEMAC modelleme sistemi ile birlikte hesap ağının oluşturulması hakkında da genel bir bilgi verilmiştir.

İstanbul Boğazı’nın fiziksel oşinografisiyle ilgili bilgiler, bu çalışmada, boğazdaki tabakalar arası iki yönlü etkileşim hakkında kabul edilmiş teoriler ile birlikte sunulmuştur. İstanbul Boğazı’nın güney çıkışını oluşturan sınır koşulunda, boğazda yapılmış en son ölçümlerin gözönünde tutulduğu yüzey ve alt akıntı ortalama debi değerleri kullanılmıştır. Bununla birlikte, boğazdaki tuzluluk tabakalaşması, hesap alanının bütününde tanımlanan başlangıç koşuluyla oluşturulmuştur.

Simulasyon sonuçlarıyla önceki arazi ölçümlerinin karşılaştırılması neticesinde, elde edilen akıntı hızı ve tuzluluk değerlerinin her iki tabaka için ölçülen arazi verileriyle oldukça tutarlı olduğu görülmüştür. Elde edilen sonuçlardan, İstanbul Boğazı’ndaki akımın kanal boyunca düşey ve yataydaki hızlı geometrik değişimlerden oldukça fazla etkilendiği doğrulanmıştır. Sonuç olarak, İstanbul Boğazı’ndaki akım değişimlerinin içsel hidroliği açısından, karışım ve tabakalaşma karakteristiklerinin temel özellikleri başarıyla açıklanmıştır.

HYDRODYNAMIC SIMULATION OF THE BOSPHORUS

ABSTRACT

In this study hydrodynamic properties of the strait of Istanbul, The Bosphorus, were modeled with three-dimensional computer code named TELEMAC-3D. Hydrodynamic properties were solved with three-dimensional Navier-Stokes equations and the governing equations, parameters, and boundary conditions were explained in this study. General information about the TELEMAC modeling system including the mesh generation was also given in this study.

Information about the physical oceanography of The Bosphorus Strait is presented in the study with the accepted theories on the two-way exchange flow within the strait. By considering the recent hydrographic observations obtained in the Bosphorus Strait, the mean values of the discharges of the surface layer and the bottom layer flows are used to establish the boundary condition forming the southern exit. In addition, the salinity stratification within the strait, is performed by using an initial condition throughout the computational domain.

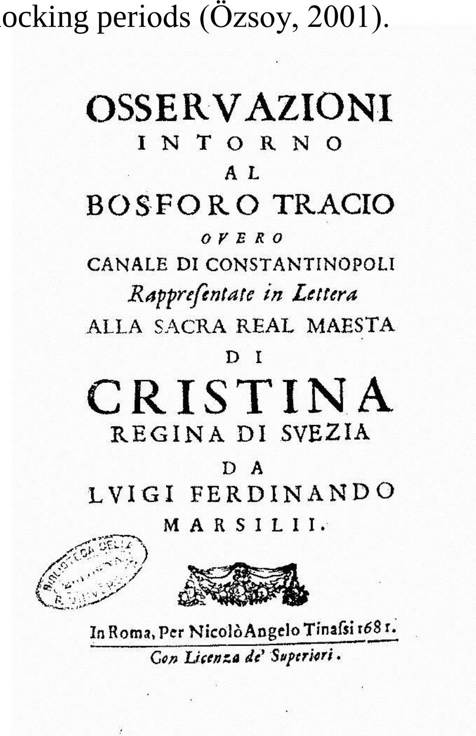
Comparing the results of the simulation with previous field measurements shows that the values of the current speeds and salinities of the two layers are similar to field study data. The simulation results also confirm that the flow within the Bosphorus Strait is much impressed by the rapid along-strait variations in the geometry of both vertical and horizontal planes. Consequently, the simulation results explain successfully the basic features of the mixing and stratification characteristics in terms of internal hydraulics of the exchange flow in the Bosphorus Strait.

1. INTRODUCTION

The Turkish Straits System TSS, consisting of the Bosphorus and Dardanelles Straits and the Sea of Marmara, provides the only mechanism of communication between the Black and the Mediterranean Seas. The TSS is located in a region with demonstrated sensitivity to climatic changes and contrasts (Özsoy, 1999), and it is also capable of driving environmental changes in the adjacent basins disproportionate to its relative size. Among the two Straits, the Bosphorus plays a predominant role, determining local transport and exchange.

The Bosphorus has been a very critical transition because of its highly important features regarding both environmental and economical aspects. Considering the environmental features, the Bosphorus has always attracted scientist's attention on the hydrodynamics of the flow through the strait.

In the 17th century, Count Marsigli was the first one to make scientific observations in the Bosphorus and to perform insightful experiments, establishing the existence of counter-currents underneath the surface currents Fig. (1.1a-b), but occasionally obscured by incomplete observations, only to be recovered later by additional measurements. Modern observations have revealed persistent exchange flows, despite short-term blocking periods (Özsoy, 2001).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DI
CRISTINA
REGINA DI SVEZIA
DA
LVIGI FERDINANDO
MARSILII.

In Roma, Per Nicolò Angelo Tinassi 1681.
Con Licenza de' Superiori.

Fig. (1.1a): The cover of study of Luigi Ferdinando Marsigli at 1681.

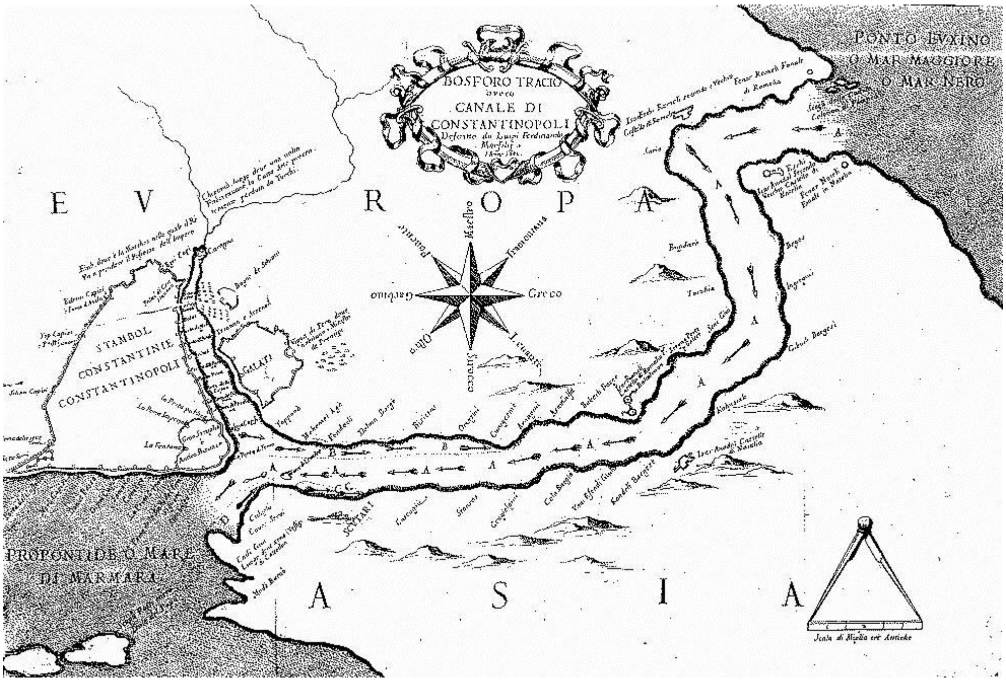

Fig. (1.1b): The surface flow reflecting the measurements of Marsigli.

The present study aims for a better understanding of the behavior of Bosphorus Strait flows based on a realistic three-dimensional model of its dynamics. In this study, the three-dimensional hydrodynamics of the Bosphorus Strait flow is established through a simulation with using the TELEMAC-3D modeling software that is a part of the TELEMAC modeling system.

Before constituting the computational domain of the Bosphorus for the simulation, general information about the Bosphorus Strait is given in Chapter2. The geometrical features including the bottom topography of the strait will be examined for their effects on the flow of the Bosphorus. The recent accepted theories developed for the two-way exchange of the stratified flow and related hydrographic characteristics are also discussed in terms of internal hydraulics in the second part of the Chapter2.

In Chapter3, a presentation of TELEMAC-3D, covering general information about the software is made and its situation in the processing chain of the general TELEMAC modeling system is introduced. In this chapter, the theoretical aspects of the equations and the parameters that are used by the computer code of the TELEMAC-3D software are given. Creating a mesh covering the computational domain that forms the first step is also given. In this chapter, it is intended to cover the understanding of the procedure from inputting data to the programmer to outputting the results after the computation.

In Chapter4, the modeling of the Bosphorus Strait is presented via defining the boundary conditions of the computational domain and creating the initial conditions of the free surface water levels on both sides of the strait and the salinity stratification along the Bosphorus Strait.

Chapter5 presents the outputs of the simulation including the horizontal and vertical cross-sections that are taken along the strait. Comparisons between these results and the data of the measurements of the recent surveys are taken place to confirm the model of the Bosphorus flow.

2. PHYSICAL OCEANOGRAPHY OF THE BOSPHORUS

2.1. General Review

The Bosphorus Strait is among the major components of the Mediterranean-Aegean-Dardanelles-Marmara-Black Sea system through which exchange of water between the Mediterranean and Black Seas occurs. It constitutes a pathway between these two basins.

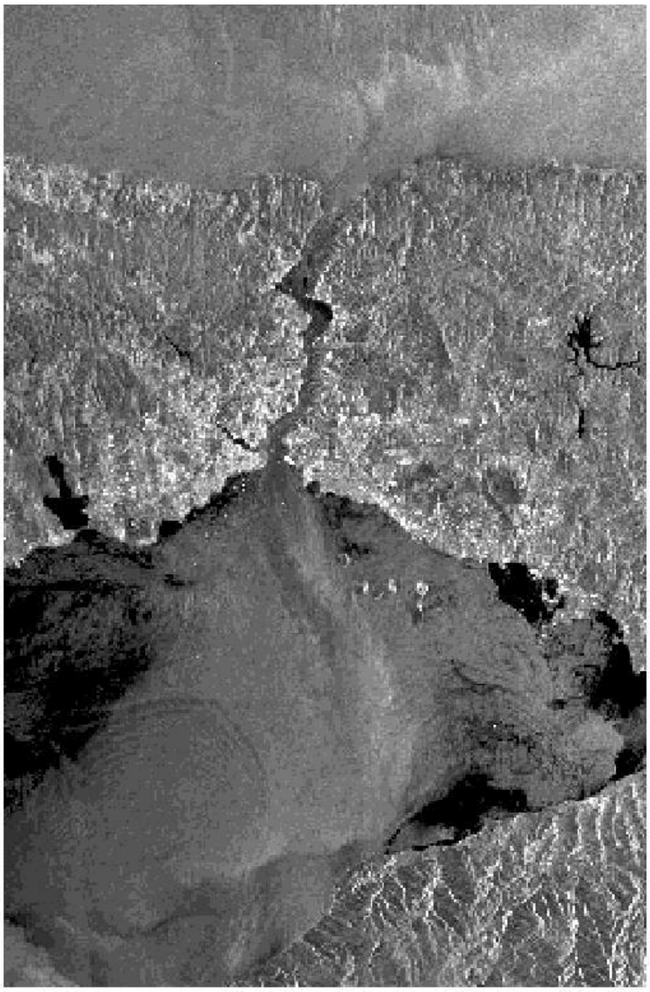

Fig. (2.1): ERS-1 SAR image of the Bosphorus Strait and the adjoining Marmara and Black Sea regions, 25 October 1995, 8:49 GMT.

Main flow features of the Bosphorus Strait are visualized by making use of Synthetic Aperture Radar (SAR) data in Fig. (2.1) above. The southward-flowing surface jet issuing into the Marmara Sea from the Bosphorus impinges on the south coast, exciting an internal wave packet visible on the surface. The SAR sensitively detects surface roughness changes resulting from currents (Özsoy et al, 2001). A conspicuous curved feature extending north from the Bosphorus joined with a wider shadow further offshore in the Black Sea coincides well with the location of the submerged Mediterranean outflow.

The Bosphorus Strait is essentially a narrow, elongated and shallow channel of nearly 31km length. Its width varies between 0.7 and 3.5km with an average value of 1.3km at the surface. The width reduces gradually towards the bottom of the channel to a typical average value of 500m at a depth of 50m. The depth varies in the range of 30 and 100m [Fig. (2.2)]. Significant cross-channel variations make it difficult to assign an average depth for a given cross section. An approximate value of 50m may, however, be considered as a representative average depth along the central section of the channel.

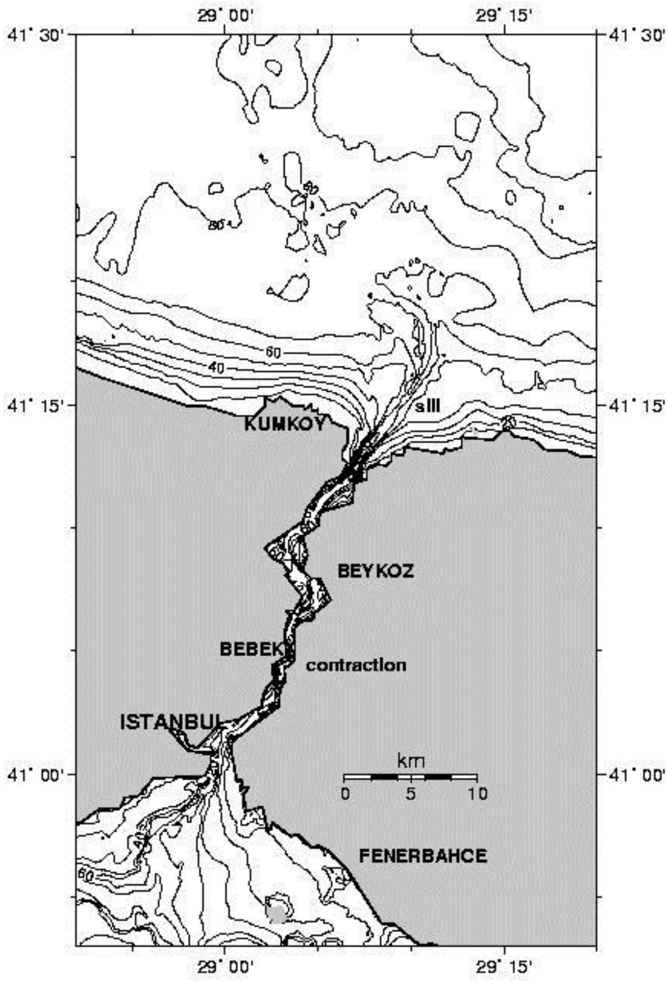

Fig. (2.2): Bathymetry map of the Bosphorus Strait.

As stated before, the Bosphorus Strait has significant variations in width and depth along its length. A well-defined constriction region located within the southern half of the Strait is one of its distinguished geometrical features. Going towards south along the Strait and disregarding the small-scale bays and embayments along both coasts, the constriction region starts at the Emirgan-Kanlıca section and continues to the south of the Arnavutköy-Vaniköy section. It, therefore, comprises a length of approximately 2,5km with the maximum constriction having a width of 600m in the proximity of Kandilli-Bebek section, coincident with the maximum depth of approximately 110m. Here, the flow in both layers speed up, and surface currents can reach a maximum of up to 2m/sec in the narrow section (Özsoy et al, 1998). As the Strait extends on both sides of the constriction region in a meandering fashion, its width expands abruptly at both ends so that the junctions to the Marmara and Black Seas occur as abrupt terminations of the channel at straight coasts.

In addition to these significant features associated with the width variations, two sills located near the entrance regions on both sides are additional potentially active regions influencing the flow characteristics within the Bosphorus. The sill found at immediately north of the Marmara junction [Fig. (2.3)] varies between minimum and maximum depths of 28m and 34m, respectively, and allows passage through two channels on both sides. On the Anatolian side of the sill, along the Üsküdar coast, the channel having a depth of about 40m is also blocked off downstream by a shallower area with a sill depth of 34m. This channel gradually deepens beyond the sill towards the south and eventually joins the submarine canyon found in the junction region of the Bosphorus and the Marmara Sea.

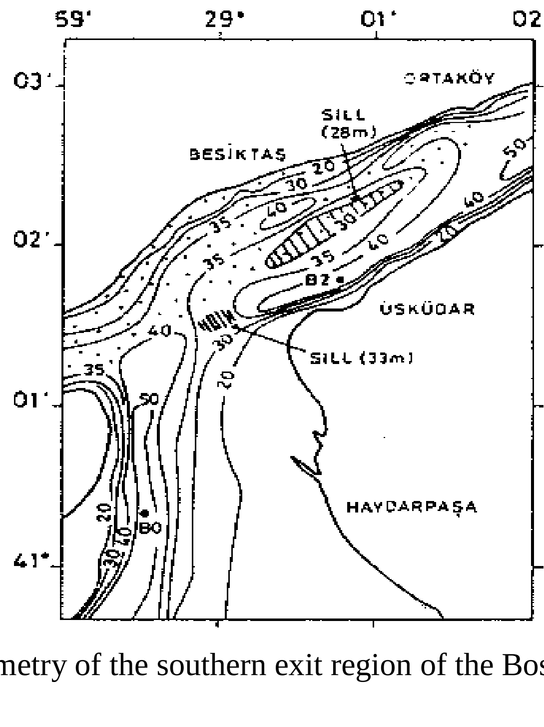

Fig. (2.3): Bathymetry of the southern exit region of the Bosphorus Strait.

The other sill is located just outside of the Black Sea termination of the Strait and has a depth of 60m and a length of about 2km [Fig. (2.2)]. It lies within the narrow channel, which occurs as a natural extension of the Strait into the Black Sea. To the north of the sill, the channel deepens gradually to 75-80m and then joins eventually to the shelf region of the western Black Sea basin. The exact location of the northern sill and details of the bathymetrical characteristics of the region surrounding the Bosphorus-Black Sea junction that have been established by recent field studies are shown in Fig. (2.4a-b). While the northern sill and the details of the narrow channel play a crucial role in determining the nature of the lower layer outflow into the Black Sea, the southern sill together with the abrupt widening of the Strait at the Marmara exit, has important implications on the form of the surface flow issuing from the Strait as well as on the mixing and turbulence characteristics of the waters in the exit region (Özsoy et al, 1988).

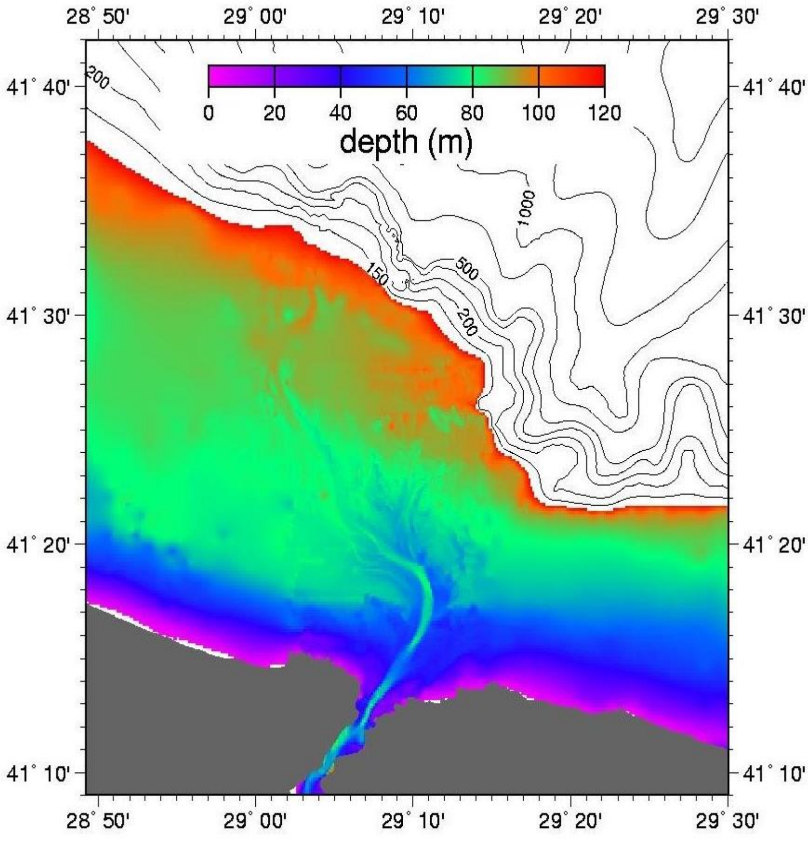

Fig. (2.4a): The bottom topography of the Bosphorus adjacent to Black Sea generated from a combined data set obtained from different sources (Özsoy et al, 2001): (i) digitized depth contours of UNESCO topographic maps for the Black Sea, (ii) digitized data from local hydrographic maps, (iii) ADCP depth measurements from R/V BILIM cruise path in September 1994, (iv) high-resolution topographical data derived from the SWATH echo-sounder on board R/V ALLIANCE in 1995

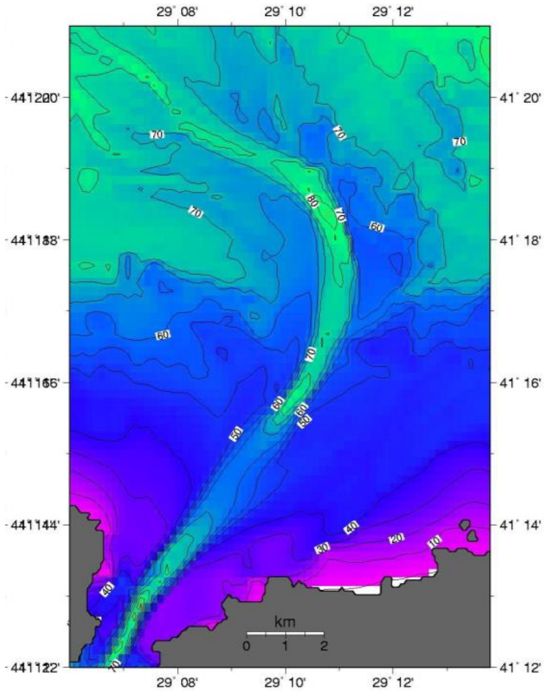

Fig. (2.4b): Bottom topography of the Bosphorus exit region, displaying features the northern sill and canyon.

The accepted theories on the two-layer flow that will be described in the following section in the Bosphorus assume that these three critical sections, which are described above, control the flow through the strait. Akyarlı and Arısoy (1995) schematized the hypothetical control sections and general features derived from various surveys in the Bosphorus as shown in Fig. (2.5).

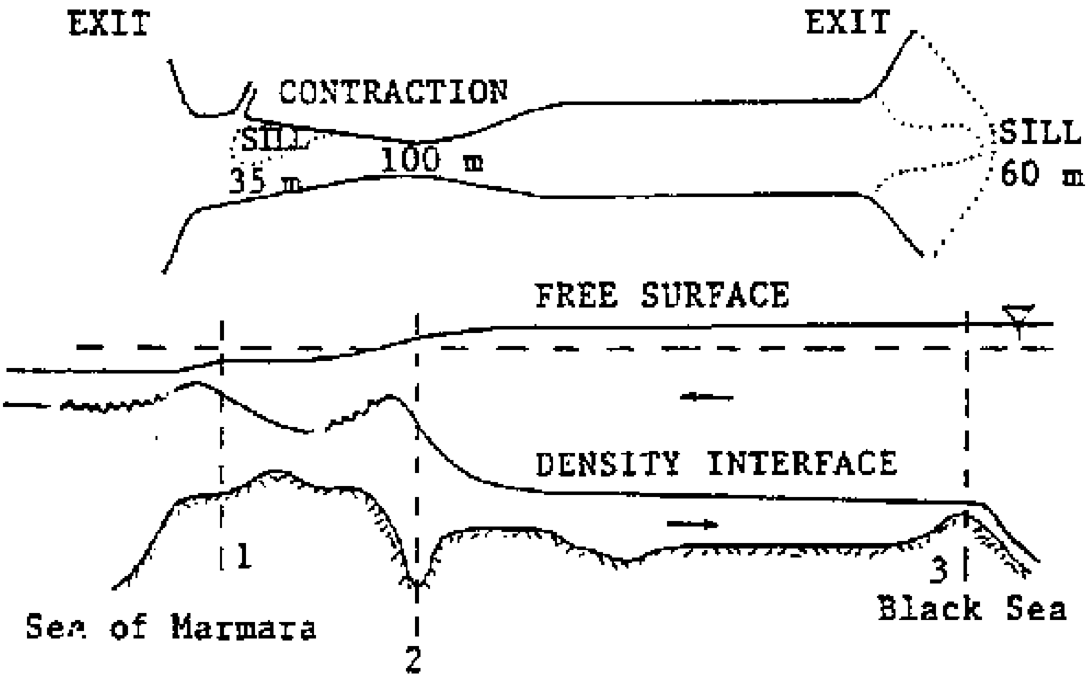

Fig. (2.5): Two-layer controlled flow schematization of the Bosphorus.

2.2. Two-layer Exchange Flow in the Bosphorus Strait

The Bosphorus Strait possesses a well-defined two-layer stratification flow and associated a two-layer system of exchange. The barotropic flow that is driven by the sea level difference between its two ends flows from north (the Black Sea) to south (the Marmara Sea) and forms the upper layer. The sea level difference varies, on the average, in the range of 20-40cm, with small tidal oscillations of the order of 10cm. The northward baroclinic flow, on the other hand is driven by the difference in density (which is predominantly governed by the salinity) between the Marmara and Black Seas. Consequently, relative dense water of the Marmara Sea flows towards the Black Sea and forms the lower layer of the strait.

The Bosphorus and the Dardanelles Straits and the Sea of Marmara constitute a system through which exchange of these Mediterranean and the Black Sea waters takes place. An assessment of the volume fluxes for the various elements of the system, based on recent hydrographic investigations, shows that a major portion of the Mediterranean flow entering through the Dardanelles is transported back to the Aegean Sea due to upward mixing induced by internal hydraulic adjustments of the exchange flow in the straits and by wind in the Sea of Marmara proper. The jet-like Bosphorus outflow in the exit region of the Marmara Sea also has a substantial contribution to the overall upward mixing. Hydraulic controls in the Bosphorus strait result in a maximal exchange, while a sub maximal exchange exists in the Dardanelles. The Mediterranean inflow enters the Black Sea on an essentially continuous basis, with only few, short interruptions (Ünlüata et al, 1990).

Recent hydrographic observations obtained in the Bosphorus Strait illustrate several features of the flow that may be related with the internal hydraulics. The two-way exchange flow may indeed be subject to a series of internal hydraulic adjustments along the strait due to morphological features such as sills, a contraction and abrupt expansion of the width of the strait. There are three distinct regions of the supercritical flow. The lower-layer flow of the Marmara Sea origin is directed to the north towards the Black Sea in a progressively thinning layer and is controlled by the sill located near the Black Sea entrance of the strait. The upper-layer water of the Black Sea origin flows in the opposite direction and is controlled upon reaching the constricted region located about 10-12 km away from the Marmara end of the strait. The upper-layer flow is then matched to the subsequent subcritical conditions by undergoing an internal hydraulic jump and becomes subject to another critical transition near the abruptly widening exit section into the Marmara Sea. The controls exerted by the northern sill and the contraction are connected by a subcritical region whereas the supercritical conditions downstream of these controls isolate the two way exchange from the conditions in the adjacent regions. In this way, the requirement for the maximal exchange is met implying that the Bosphorus Strait achieves the maximum possible transports in the layers depending on the magnitude of net barotropic transport (Oğuz et al, 1990).

2.2.1. Theoretical Approach to the Two-Layer Exchange

Rotating hydraulic theories are often used to investigate the effect of geometrical obstructions on the flow through straits. The rotational hydraulics theories are, in fact, valid for a channel whose width should be comparable with the internal Rossby radius of deformation:

$$R = (g^1.h)^{1/2}/f \tag{2.1}$$

In the equation (2.1) f, h and g^1 denote the Coriolis parameter, the depth of the water column and the reduced gravity, respectively. In the case of the Bosphorus, the width is typically an order of magnitude smaller than R implying that the effect of rotation is negligible and therefore, the classical nonrotating hydraulics should be applicable. Among others, the most detailed analysis of nonrotating two-layer hydraulic flow is studied by Farmer and Armi (1986).

Özsoy et al. (1988) suggested that the Bosphorus flow might be subject to hydraulic transitions at the constriction region combined with the southern end of the Strait and the northern sill. Based upon numerical model computations, Oğuz et al. (1990) studied the nature of the exchange in the strait and hydraulic controls by examining the steady state along channel variation of the composite Froude number. The composite Froude number G^2 is defined by Farmer and Armi (1986) as;

$$G^2 = F_1^2 + F_2^2 \tag{2.2}$$

With the equation below F_k is named as the densimetric Froude number.

$$F_k = U_k/(g^1D_k) \ (k = 1,2) \tag{2.3}$$

In the equation (2.3) g^1 is defined as below.

$$g^1 = g\ (\rho_2 - \rho_1)/\rho_2 \tag{2.4}$$

In the equations U_k, D_k, ρ_k are current speed, thickness and density of the upper (k=1) and lower (k=2) layer. The densimetric Froude number expresses the ratio of kinetic to potential energy of the flow. Hydraulic control occurs when the flow is critical, corresponding to the condition $G^2 = 1$. A control point separates subcritical flow ($G^2<1$) from supercritical flow ($G^2>1$). G^2 is also interpreted as the parameter characterizing the degree of non-linearity of the flow. According to Oğuz et al.

(1990), the lower layer of Mediterranean origin flows subcritically ($F_2^2<1$) towards the northern exit region (Yüce, 1996).

Farmer and Armi (1986), discuss the two-layer exchange flow through a channel of uniform width consisting of a sill at one end and the abruptly expanding exit at the other end and study internal hydraulics for steady, frictionless, immiscible two-layer flows as shown in Fig. (2.6). Specifically they describe how a sill (assumed to be situated adjacent to the deep reservoir from which the brackish surface layer flow of the channel is originated) and contraction or abrupt expansion of the channel width (the reservoir containing the denser water lies outside the channel) found at its two ends altogether to constrain the exchange flow and consequently lead to the conditions of "maximal exchange" between the basins. In this way, the supercritical conditions on either side of the control sections isolate the two-layer exchange in the channel from the conditions in the adjacent basins. Depending on the average densities of the layers, the channel geometry and the magnitude of the net barotropic flow passing through the channel, the critical controls determine the magnitude of flows in the layers and the shape of the interface.

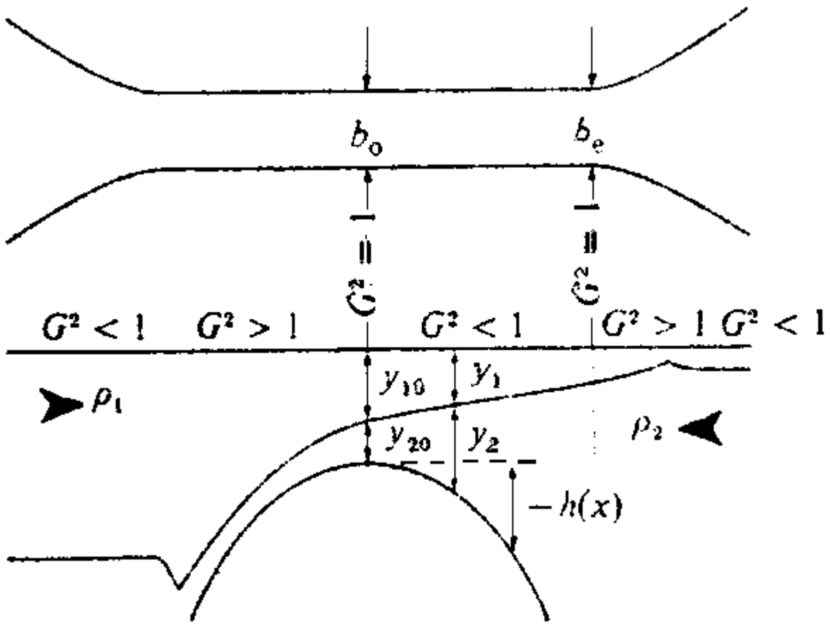

Fig. (2.6): Side and plan views for maximal two-layer exchange flow showing position of the interface.

Özsoy et al. (1998) indicate that the special setting of the Bosphorus [Fig. (2.7)], with two hydraulic controls, respectively imposed at the sill located offshore of its northern entrance, and at the contraction in the southern part, makes it one of the best examples of the "maximal exchange" regime. A contraction located between the higher density Marmara Sea and the northern sill, and suitable basin conditions, as considered by Farmer and Armi (1986), allow "maximal exchange".

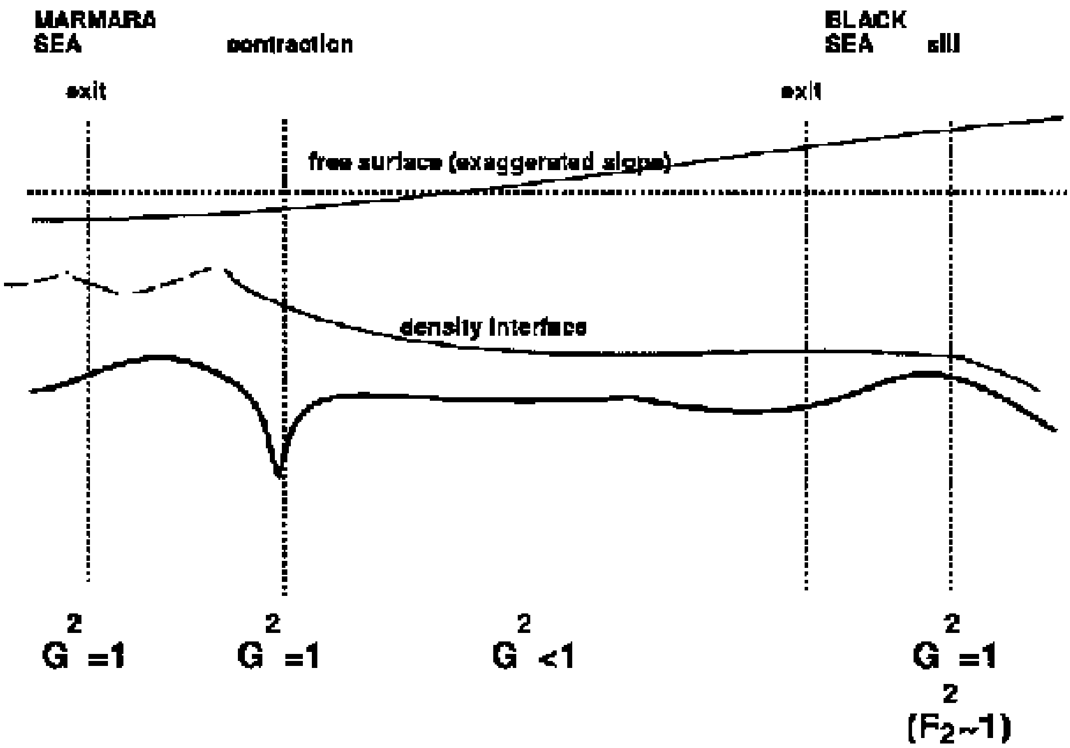

Fig. (2.7): Schematization of the Bosphorus two-layer system.

For a channel of uniform width, calculations show that the thickness of the lower layer above the sill crest is 0.375 of the sill depth in the absence of a barotropic flow component, i.e. when transport in both layers is equal but in different directions. In the presence of a net barotropic flow, the interfaces heights at the control sections as well as the layer speeds and flow rates are, however, modified. For example, for a net barotropic flow in the direction of the surface layer flow, as in the case of the Bosphorus Strait, the lower layer thickness at the sill crest and the corresponding lower layer transport are reduced with the increasing net barotropic flow (Özsoy et al, 1988).

In addition to the maximal exchange solution referred to above, there is another possible set of solutions of the system. They are referred to as the “submaximal exchange solutions” and reflect the effect of reservoir conditions on the exchange flow, which are, therefore, no longer fully determined by the conditions within the channel alone. For example, when the interface level in the high density reservoir adjacent to the exit control is sufficiently deep, the exit control is lost and the flow being critical at the sill crest is, then, matched to the high density reservoir subcritically. This case arises when the interface depth in the high density reservoir is deeper than 3/2 of its depth at the exit control. Conversely, when the interface in the low density reservoir adjacent to the sill control is sufficiently shallow, the sill control is lost and the flow in the channel is controlled both by the condition in the low density reservoir and the sill. This case occurs if the reservoir interface is shallower than 3/2 its depth at the sill control (Özsoy et al, 1988).

2.3. Hydrographic Characteristics of the Bosphorus

The two-layer stratification and associated flow structure in the Bosphorus marks temporal variations depending particularly on the intensity of the Black Sea inflow at the surface layer as well as the shorter-term changes occurring in response to the prevailing wind conditions. The two-layer stable density stratification is controlled by the salinity and the temperature stratification is relatively unimportant. Wintertime temperature structure consists of cold waters of the Black Sea origin (minimum of about 4-5^{0}C) above relatively warmer Mediterranean waters (14-15^{0}C). A different temperature structure is formed during summer months with relatively warmer surface layer waters and cold subsurface waters located above the transitional layer, overlying the bottom waters of the Mediterranean origin. The temperature near the surface may reach 24^{0}C, whereas an inversion layer of cold subsurface Black Sea waters, unaffected by radiational heating, attain typical temperatures about 9-10^{0}C. The salinity of the upper layer varies between 16.5-18.5ppt at the northern half of the strait through out the year, with the lower values indicating summer conditions corresponding to the increased Black Sea inflow. The salinity of the lower layer waters attain a maximum value of 38.5ppt in the region to the south of the constricted area (Marmara end), and decreases progressively towards the northern exit at a rate depending on the intensity of vertical mixing (Özsoy et al, 1988).

Özsoy et al, (1988) have already remarked that the hydrographic and flow characteristics within the Bosphorus Strait are extremely transient and variable in character. Changes in the environmental conditions may induce considerable variations of different time and length scales. In addition to the sensitivity of hydrographic and flow properties to external conditions, irregular morphology of the Strait further imposes crucial constraints on the two-way exchange through the Bosphorus.

Oğuz et al. (1990) delineate the typical variations taking place in the Bosphorus Strait [Fig. (2.8)] by the salinity transects shown in Figs. (2.9a-e). In these transects, the typical flow conditions in the Bosphorus with some seasonal variations are displayed in Fig (2.9c). The cases with increased upper layer caused by extremely strong northerly winds from the Black Sea are shown in Figs. (2.9a-b). The opposite case of increased lower; reduced upper layer flows as a result of southerly winds from the Marmara Sea are presented in Figs. (2.9d-e).

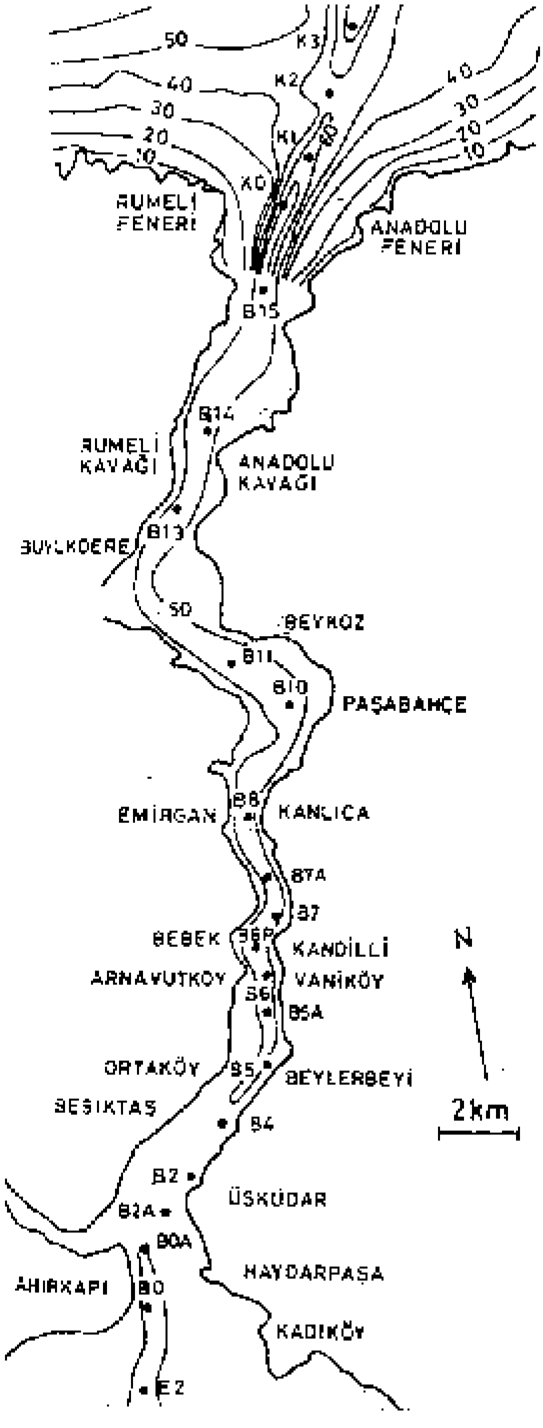

Fig. (2.8): Plan view of the Bosphorus geometry and locations of the hydrographic stations.

As may be noted in Fig. (2.9c), the interface may generally be identified by a transitional layer between the salinity limits of 18-23 and 33-38ppt. It is relatively sharper at the northern half of the strait with an average thickness of about 5m located at the depths of 40-50m. It extends with a mild slope towards to southern part (to the south of Emirgan-Kanlıca section) where significant changes take place with its position and stratification characteristics. Intense mixing of the bottom waters into the upper layer, a sharp upward tilt of the interface and the intensification of the upper layer currents characterize this region. The vertical mixing results in a total increase of about 2-3ppt in the upper layer salinity between the two ends of the Bosphorus. The salinity of the northerly flowing bottom layer waters decreases accordingly by about 2-3ppt. The interfacial zone becomes much broader as compared with further upstream and has a thickness of 20-30m. The surface layer flow eventually exits from the southern entrance in the form of a turbulent buoyant jet.

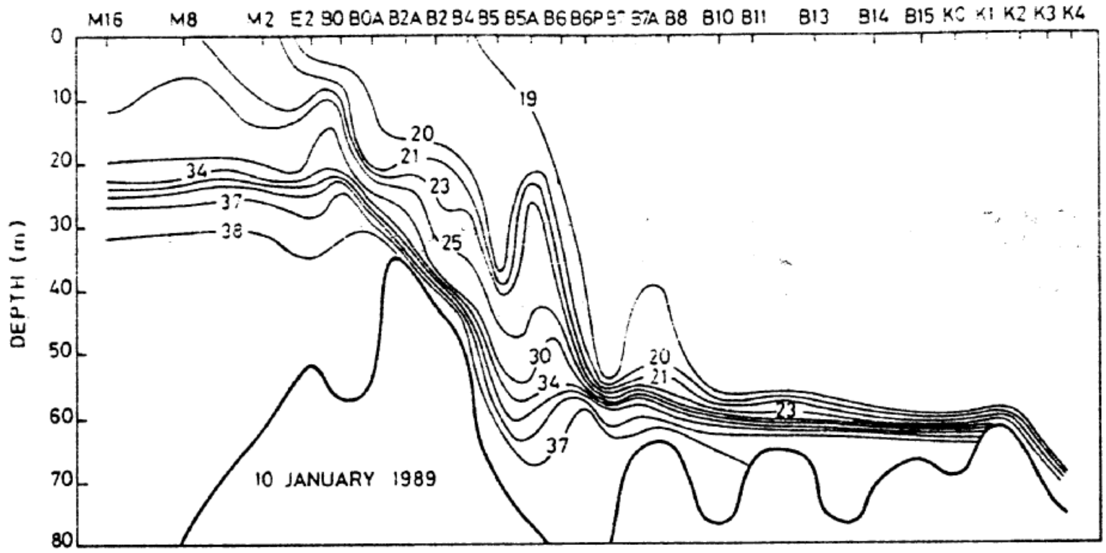

Fig. (2.9a): Salinity transect in the Bosphorus Strait for January 1989.

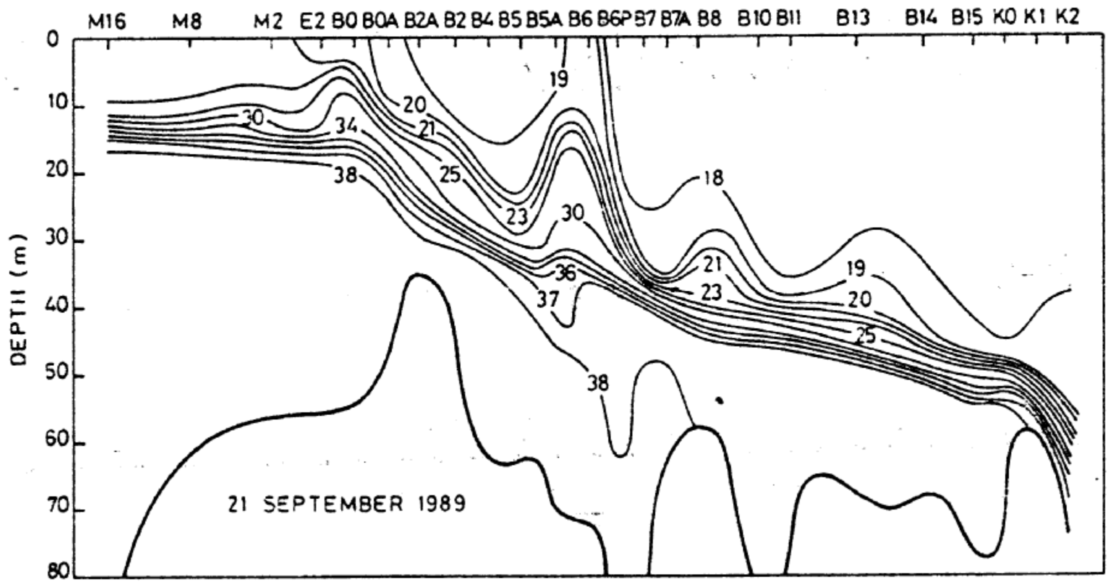

Fig. (2.9b): Salinity transect in the Bosphorus Strait for September 1989.

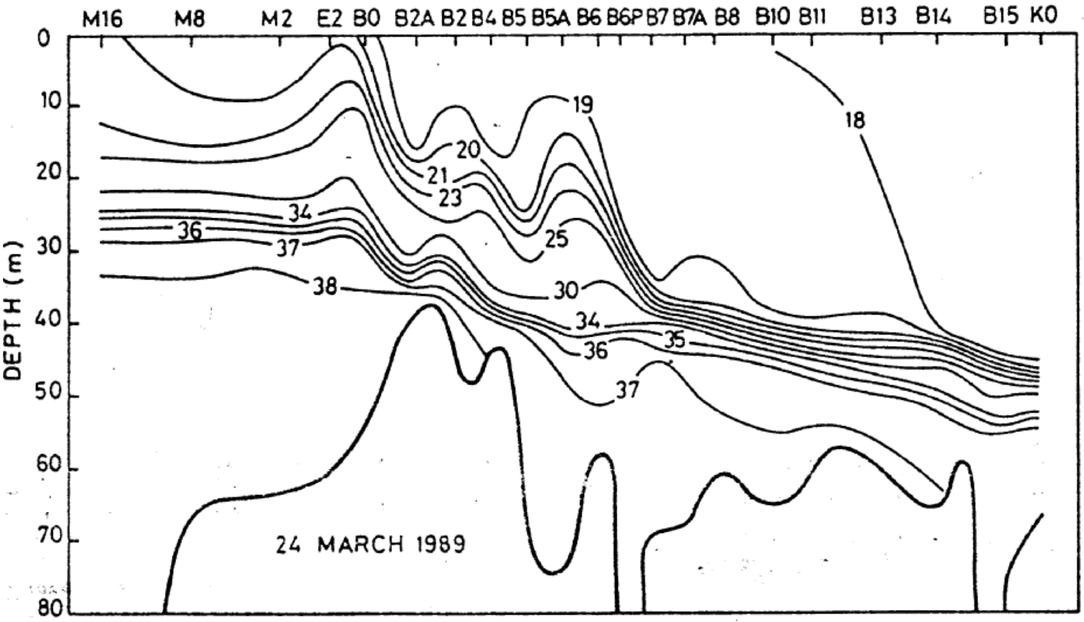

Fig. (2.9c): Salinity transect in the Bosphorus Strait for March 1989.

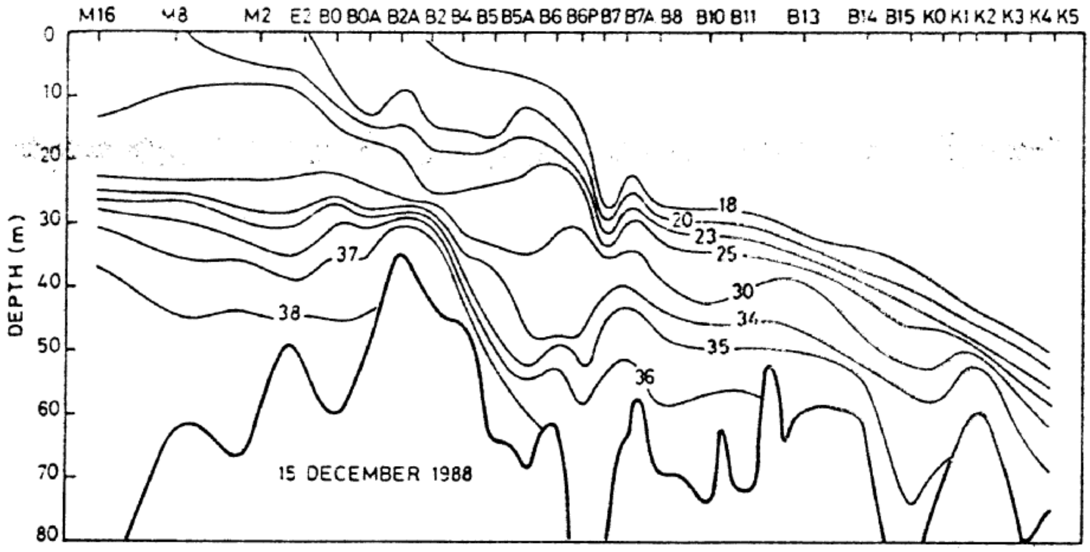

Fig. (2.9d): Salinity transect in the Bosphorus Strait for December 1988.

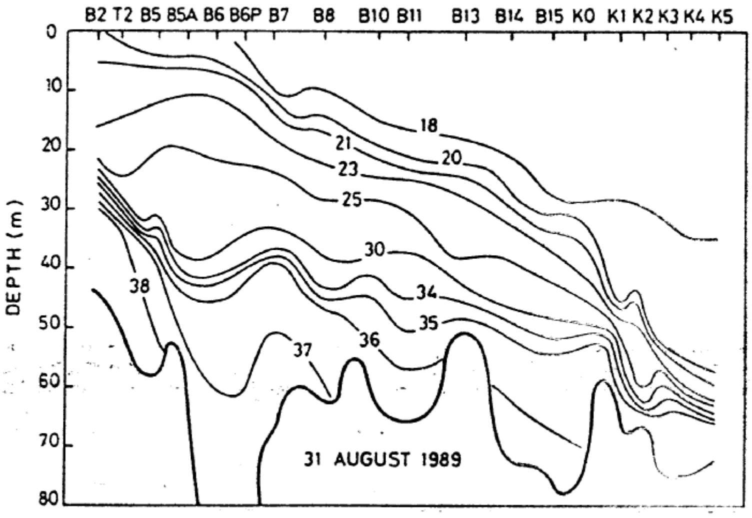

Fig. (2.9e): Salinity transect in the Bosphorus Strait for August 1989.

Fig. (2.9a) reflects an extreme case of large upper layer inflow from the Black Sea due to high northerly winds prevailing over the region. In this distinctly different case, the interface is located below a very deep, wind-induced mixed layer reaching depths of 60-65m at the Black Sea extremity, and extending almost horizontally up to the constricted region. As compared to the cases shown in Figs. (2.9b-c), where the outflow of the Mediterranean waters into the Black Sea was always insured, the high rate of surface layer inflow caused almost complete blocking of the underflow below the northern sill level. At the southern part the shape of the isohalines implies that the lower layer inflow may only be advected partially towards north and returns partially back to the Marmara Sea (Oğuz et al, 1990).

During the surveys on 13 March 1986 of the Greater Istanbul Sewerage Project, Özsoy et al. (1988) reports the similar case above. The interface is very deep, reaching to 65m depths at the Black Sea entrance as shown in Fig. (2.10).

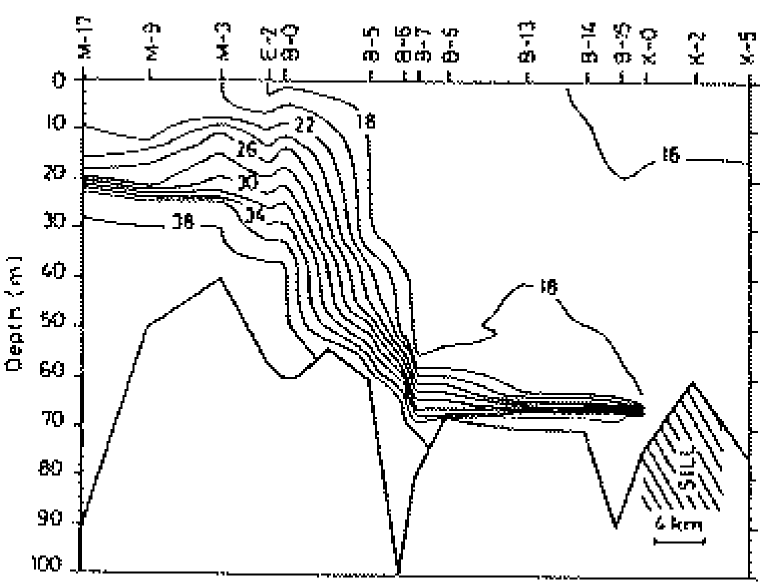

Fig. (2.10): Salinity transect in the Bosphorus Strait between M-17 (Marmara exit) and K-5 (Black Sea exit) on March 1986.

Figs. (2.9d-e) denote to cases with higher rate of vertical mixing due to the intensified lower layer inflow, and weakened upper layer flow caused by the southerly winds. Özsoy et al. (1988) encountered this kind of situation during their surveys as shown in Fig. (2.11). The southwesterly Lodos winds have very significant effects on the flow and stratification characteristics of the Bosphorus and led to the so-called Orkoz event, giving rise the reversal of the upper layer flow at some distance from its southern entrance. During the blocking of the upper layer flow, the intense flow of the Mediterranean bottom waters becomes much diluted due to strong vertical mixing and exit from the northern end with relatively lower salinities of about 32-33ppt.

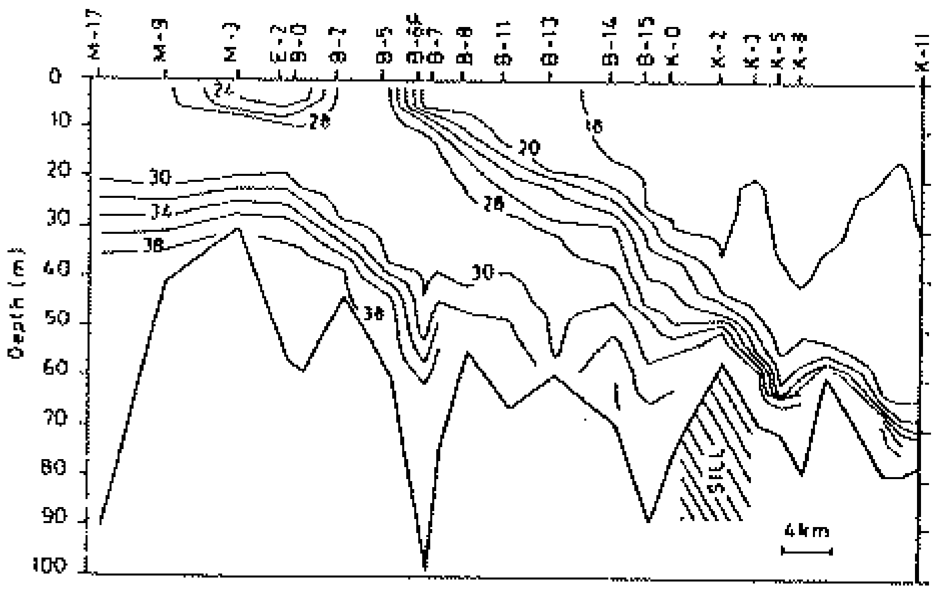
Fig. (2.11): Salinity transect in the Bosphorus Strait.

Except for the extreme case presented in Fig. (2.9e), all of the transects reveal some common features that may be associated with the internal hydraulics. In particular, as the upper layer flow passes through the constricted region, rapid changes are indicated at the position of the interface. The maximum changes occur exactly B6 and B7 located close to each other. Here the interface slopes sharply upwards by about 10-25m, suggesting possibly that the flow adjust itself to the critical condition and becomes supercritical immediately to the south of the control section. Thereafter, the sharp rise of the interface comes to an abrupt end, and the interface depth deepens to a position, which would be normally attained in the absence of controlled flow conditions. The upper layer flow thus adjusts itself to the subcritical state by undergoing an internal hydraulic jump. Increased separation of isohalines both within each layer and at the interfacial zone observed to the south of the control section implies increased vertical mixing in the supercritical regime of the upper layer flow and the subsequent internal hydraulic jump (Oğuz et al, 1990).

Following the controlled flow conditions at the constriction region, rapid changes occur again in the shape of isohalines suggesting the presence of a second controlled flow situation near the southern end of the strait. The upper layer flow accelerates in passing through the region and may be subject to internal hydraulic adjustment at this section of the strait as well as the subsequent abruptly widening exit section into the Marmara Sea. These potential controls are, in fact, so close to each other that if the flow is controlled in the sill region and becomes supercritical to the south, it may continue to be in the supercritical regime up to the Marmara exit region of the strait. In any case, their influences on the exchange flow can not be distinctly separated in the hydrographic transects, which generally show sharp and continuous rise of isohalines to the south of station B5 up to stations B0 and E2 in Figs. (2.9a-d). The strongest mixing is, however, seen at the exit region into the Marmara Sea (between stations B0 and M2). It may therefore be inferred that a second internal hydraulic jump takes place in the vicinity of the station M2 for the transition of the controlled flow to the equilibrium two-layer subcritical conditions of the Sea of Marmara.

The dense water of the Mediterranean origin having salinities of about 38ppt flows towards the north in a progressively thinner layer. After it passes over the southern sill, it appears that a hydraulic jump or finite amplitude wave forms at the downstream side of the sill depending on the intensity of the underflow and the thickness of the layer. This feature is identified by the diffusive forms of the isohalines within the lower layer near stations B5-B5A. Upon reaching the northern exit region, the underflow enters the Black Sea by accelerating over the sill in the form of a thin plume having an average thickness of about 10m. The form of isohalines implies the presence of an internal hydraulic adjustment of the lower layer flow at the sill. The Mediterranean effluent flowing downhill in the form of a density current soon reverts to the subcritical condition of the western Black Sea by undergoing an internal hydraulic jump.

As a result of these hydraulic controls, Özsoy et al (1988) reports that the two-layer water exchange between the Marmara and Black Seas will predominantly be determined by the conditions within the Bosphorus Strait, and not dictated by the conditions at the adjacent basins. Depending on the average densities of the layers, the geometry of the strait and the magnitude of the net southerly flowing barotropic flow, the critical controls will determine approximately the shape of interface establish in the Bosphorus and the magnitudes of flows in the layers entering into the Strait from the upstream basins. However, the interfacial mixing taking placing at the supercritical and internal hydraulic jump regions as well as the internal friction between layers could lead to some modifications in this basic structure of the two-layer exchange flow through the Strait.

3. TELEMAC-3D MODELING SYSTEM

The TELEMAC-3D software solves 3D hydraulic equations (with the assumption of hydrostatic pressure conditions and time-dependent surface) and transport-diffusion equations for intrinsic values (temperature, salinity, concentration). The main results obtained at each point of the computational mesh are velocity in three directions and the concentration of transported quantities. The main result for the surface mesh is the water depth. The main applications of TELEMAC-3D are in free-surface maritime or estuarine hydraulics. It takes the following phenomena into account:

- Influence of temperature or salinity on density.
- Bottom friction.
- Influence of Coriolis force.
- Influence of meteorological conditions: atmospheric pressure and wind.
- Consideration of heat exchanges with the atmosphere.
- Fluid and momentum sources and sinks within the domain.
- Simple or complex (k-epsilon) turbulence models including effects of Archimedes' force (buoyancy).
- Dry zones within the computational domain: tidal flats.
- Tracer transport and diffusion by the current, with creation or disappearance terms.

The software has many fields of application, the main ones being in maritime studies, especially in relation to currents generated by the tide or by density gradients, with or without external forcing due to wind or air pressure. It may be applied to large areas (at the scale of a sea) or more restricted ones (coastal and estuarine areas) to study the impact of a coastal outfall, thermal plumes or sediment transport.

TELEMAC-3D was developed by the Laboratoire National d'Hydraulique (LNH), part of the Studies and Research Division (DER) of Electricité de France (EDF). TELEMAC-3D is integrated in a processing chain - the TELEMAC system. This contains all the modules required to build a model and perform hydrodynamic, contaminant transport and sediment transport simulations.

The TELEMAC system consists of the following modules, as shown in Fig. (3.1):

- The SINUSX software, which is used, with a digitising table, to enter the bed and contour of the model domain. The file created by this module is then reread by the mesh generation system.
- The MATISSE software is used to build the grid based on triangular elements, using the bathymetry.
- The STBTEL software, which rereads the file derived from the mesh generator, interpolates any bathymetric information, and creates a geometry file to the Selafin standard that can be read by the simulation models and by the RUBENS program. STBTEL performs a number of mesh consistency checks.
- The EDAMOX software, which is used interactively to create the steering files required for the various computation modules.
- The TELEMAC-2D software, which is used to perform hydrodynamic simulations of 2D flows.
- The TELEMAC-3D software itself, which is used to perform hydrodynamic simulations of 3D flows.
- The SUBIEF software, which is used to simulate the transport of suspended sediments in 2D flow conditions, and calculate the transport of dissolved substances without gravity effects.
- The TSEF software, which is used for simulating bed load transport in 2D flow conditions.
- The ARTEMIS software computes the transformation of wave characteristics in a coastal area or harbour.
- The POSTEL-3D software, which is used for post-processing the 3D results from TELEMAC-3D, in the form of 2D cross-sections, to be visualised with RUBENS.
- The RUBENS software, which is used for exploiting the results from the various simulation modules in graphic form.

The modules used at Technical University of Istanbul during the hydrodynamic simulation of the Bosphorus are the MATISSE (mesh generator), TELEMAC-3D, POSTEL-3D and RUBENS, respectively. The ARTEMIS and TELEMAC-2D software are also used by the working group of Tubitak project at the university to investigate the effects of long waves like Tsunamis on the north coast of the Marmara Sea.

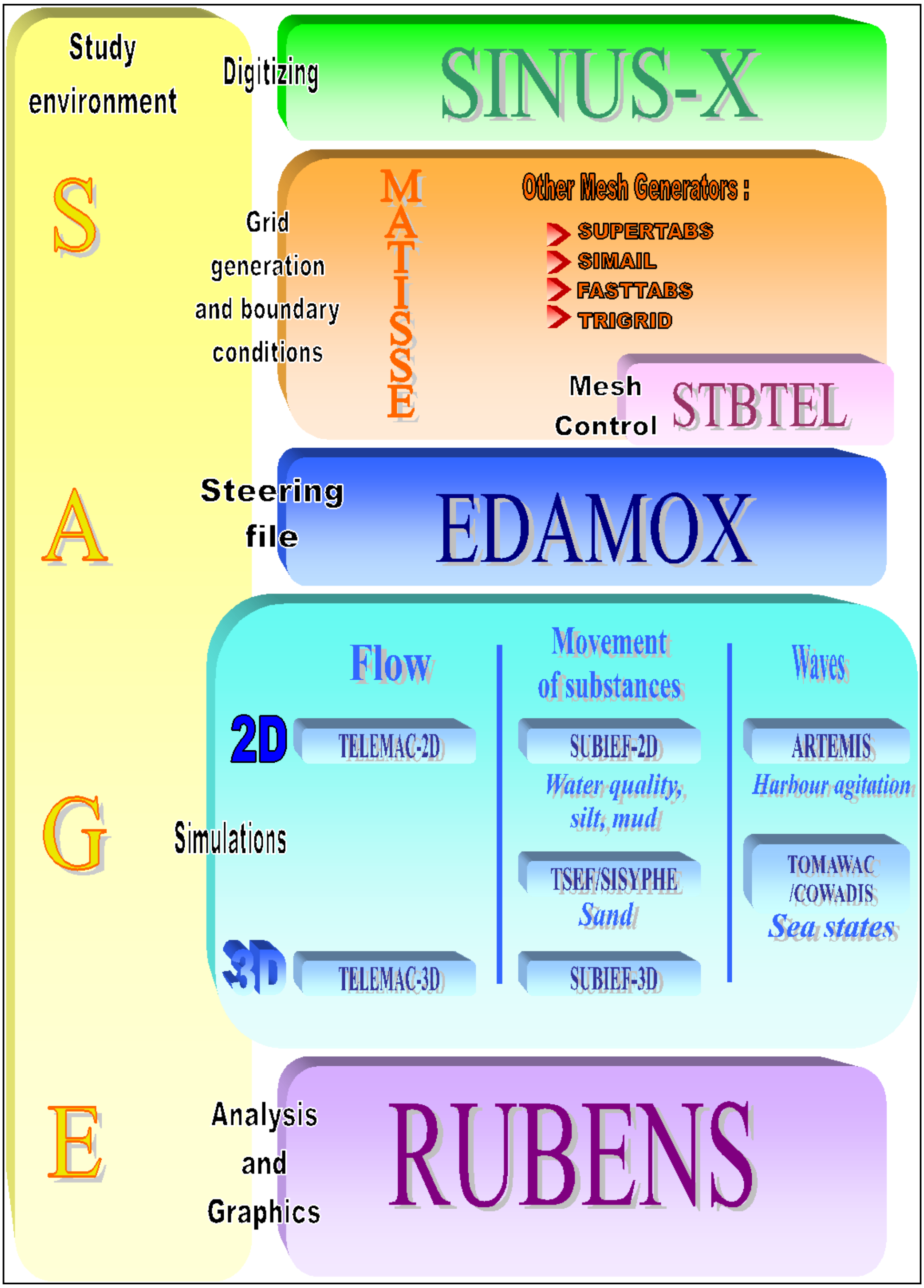

Fig. (3.1): TELEMAC Modeling System.

3.1. Theoretical Aspects

3.1.1. Notations

TELEMAC-3D is a three-dimensional computation code that describes the 3D velocity field (u, v, w) and water depth h (or free surface S measured from the bed) at each time step. It also solves the transport of several tracers grouped into two categories: the so-called “active” tracers (mainly temperature and salinity) that act on the density of the water and hence on flow, and the so-called “passive” tracers which do not act on the flow and are simply transported.

3.1.2. Equations

The code solves the three-dimensional hydrodynamic equations under the following assumptions:

- Navier-Stokes 3D equations with free surface changing in time,
- negligible density variation in the mass conservation equation,
- hydrostatic pressure assumed,
- Boussinesq approximation for momentum.

Considering these assumptions, the following 3D momentum and transport equations are given as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1\partial p}{\rho\partial x} + \frac{\partial}{\partial x}\left(\upsilon_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(\upsilon_H\frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\upsilon_z\frac{\partial u}{\partial z}\right) + Fx \tag{3.1}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1\partial p}{\rho\partial y} + \frac{\partial}{\partial x}\left(\upsilon_H\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial y}\left(\upsilon_H\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\upsilon_z\frac{\partial v}{\partial z}\right) + Fy \tag{3.2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{3.3}$$

$$p = \rho_0 g (S - z) + \rho_o g \int_z^S \frac{\Delta\rho}{\rho_0} dz \tag{3.4}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(\nu_{HT}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\nu_{HT}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\nu_{zT}\frac{\partial T}{\partial z}\right) + Q_T \tag{3.5}$$

With:

h	(m)	water depth.
S	(m)	free surface elevation.
u, v, w	(m/s)	velocity components.
T	(°C)	active or passive tracer
p	(kgf/m^2)	pressure.
g	(m/s^2)	acceleration due to gravity.
ν_H, ν_Z	(m^2/s)	velocity diffusion coefficients.
ν_{HT}, ν_{ZT}	(m^2/s)	tracer diffusion coefficients.
Z_f	(m)	bottom elevation.
ρ	(kgf/m^3)	density.
$\Delta\rho$	(kgf/m^3)	variation in density.
t	(s)	time.
x, y, z	(m)	horizontal space components.
Fx, Fy	(m/s^2)	source terms.
Q	(tracer unit)	tracer source or sink.

h, u, v, w and T are unknowns, also referred to as computation variables.

Fx and Fy are source terms representing the wind, Coriolis force and bottom friction. Several tracers may be taken into account at the same time. They may be of two different types, either active, i.e. influencing flow by modifying the density, or passive, with no effect on the density and hence on flow.

The hyperbolic and the parabolic parts of the Navier-Stokes-equations are treated separately by TELEMAC-3D code in order to use well-adapted numerical methods for each part. This implies that the hyperbolic part i.e., the advection terms are treated using characteristic methods, and the parabolic part i.e., the diffusion terms using finite elements.

The water depth is calculated by integrating the pressure-continuity terms along the vertical. The resulting 2D equations are written:

$$\frac{\partial h}{\partial t}+\frac{\partial \bar{u}h}{\partial x}+\frac{\partial \bar{v}h}{\partial y}=a \tag{3.6}$$

$$\frac{\partial \bar{u}}{\partial x}=-g\frac{\partial S}{\partial x}+\bar{F}_x+\bar{S}_x \tag{3.7}$$

$$\frac{\partial \bar{v}}{\partial y}=-g\frac{\partial S}{\partial y}+\bar{F}_y+\bar{S}_y \tag{3.8}$$

In the Eq. (3.6), generally a is equal to zero except in the presence of a bottom outfall. The over-scored letters indicate the corresponding vertically integrated 3D variables in the equations. $\bar{F}_x$ and $\bar{F}_y$ are the vertically averaged buoyancy terms (Coriolis force, bottom friction, influence of the wind) and $\bar{s}_x$ and $\bar{s}_y$ are the other vertically averaged source terms (atmospheric pressure, sources of momentum).

3.1.2.1. The Bottom Friction Definition

The law that TELEMAC-3D uses to model bottom friction is a quadratic function of the flow, assuming a turbulent boundary layer with a logarithmic profile. This law includes the representative depth D of bottom roughness (particle size). D can be connected to Chézy's coefficient by the relation:

$$Ch=\frac{26.4}{D^{1/6}}\left(\frac{D}{h}\right)^{1/24}h^{1/6} \tag{3.9}$$

There are three possible choices for defining the friction parameter:

- Smooth conditions, no friction
- Rough, with size of roughness
- Rough, with Chézy's coefficient

3.1.2.2. Coriolis Force

When modeling large areas, it is necessary to take into account the inertia effect of the Coriolis force. This is calculated in accordance with the latitude λ at a point by the formula:

$$\begin{aligned} F_x &= 2\omega v\sin\lambda = fv \\ F_y &= -2\omega u\sin\lambda = -fu \end{aligned} \tag{3.10}$$

$$f=2\omega\sin\lambda \tag{3.11}$$

In small domains, the coefficient defined in the Eq. (3.11) is considered a constant and it is the "Coriolis coefficient" input for TELEMAC-3D computation.

For example, the computational domain, the Bosphorus Strait is on the 36th latitude and considering the angular velocity of the earth ω as 7.292 x 10^{-5} rd/s (there are π radians in a sidereal day, equal to 0.997270 days of 24 hours, that is, 86164 s), the Coriolis coefficient then can be calculated as:

f = 2 x 7.292 x 10^{-5} x sin(36) = 0.857 x 10^{-4} N m^{-1} s.

3.1.2.3. Influence of Wind

Analogous to the analysis of friction at the bottom, the resistance of the wind takes the following form with neglecting the slope of the free surface:

$$F_x = \frac{1}{h}\frac{\rho_{air}}{\rho} a_{vent}\ U_{vent}\ \sqrt{U_{vent}^2 + V_{vent}^2}$$
$$F_y = \frac{1}{h}\frac{\rho_{air}}{\rho} a_{vent}\ V_{vent}\ \sqrt{U_{vent}^2 + V_{vent}^2} \qquad (3.12)$$

In Eq. (3.12), a_{vent} is a wind-resistance coefficient and U_{vent}, V_{vent} are the components of the wind velocity on the computation domain in m/s and ρ_{air}/ρ is the ratio of the air and water densities.

The coefficient a_{vent} hides complex phenomena. In fact, the influence of the wind depends on the smoothness (or, lack of it) of the free surface and the distance over which it acts (called the "fetch"). Value of a_{vent} can be obtained from many different formulas. The TELEMAC-3D software uses the following formula used by the Institute of Oceanographic Sciences (United Kingdom):

If $|\vec{U}_{vent}| < 5$ m/s:

$$a_{vent} = 0{,}565\ 10^{-3} \qquad (3.13)$$

if $5 < |\vec{U}_{vent}| < 19{,}22$ m/s:

$$a_{vent} = (-\,0{,}12 + 0{,}137\ |\vec{U}_{vent}|)\ 10^{-3} \qquad (3.14)$$

if $|\vec{U}_{vent}| > 19{,}22$ m/s:

$$a_{vent} = 2{,}513\ 10^{-3} \qquad (3.15)$$

ρ_{air} is approximately 1.023 kg/m^3 and ρ is taken as 1000 kg/m^3 in the equations stated above.

3.1.3. The Mesh

The structure of the TELEMAC-3D mesh consists of prisms. The first stage is to construct a 2D mesh consisting of triangles that cover the domain horizontally. Secondly, this is reproduced along the vertical, following a number of curved surfaces, referred to as "planes". The links between repeated triangles in two planes of this type form the prisms. In Fig. (3.2), there can be seen the three-dimensional mesh consisting of prisms.

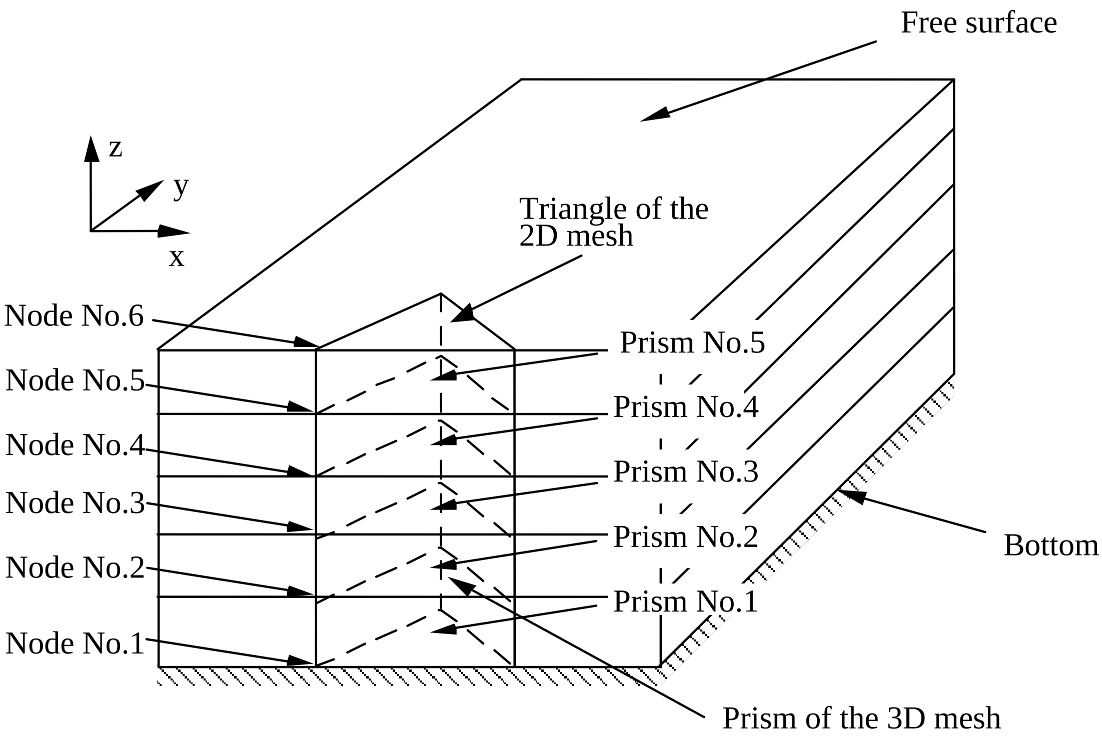

Fig. (3.2): The three-dimensional mesh of a computation domain.

It should be noted that the computation variables (see section 3.1.1) are defined at each point of the 3D mesh, including the bottom and surface. These are thus "three-dimensional variables", with the exception, however, of the water depth and bottom elevation, which are obviously defined only once along a vertical. They are thus "two-dimensional variables".

In the Telemac system, the mesh is created by the MATISSE software. The MATISSE software is used to build the grid based on triangular elements, using the bathymetry data representing the region. It also allows defining the boundary conditions. The TELEMAC-3D code then uses the two files generated by MATISSE for the computation. In the following section a brief introduction to MATISSE software will be given.

3.1.3.1. MATISSE: Mesh generator

The simulation modules of the TELEMAC modeling system are based on the resolution of partial derivative equation systems through the finite element method. This method is based upon a space discrimination, namely the "mesh" [Fig. (3.2)], of the computational domain. The investigated domain can be meshed with the knowledge of geometry and hydrodynamic behaviour of the problem to be handled. For example:

- the outside contour of the computational domain,
- the islands within the domain,
- geometric items to be taken into account, e.g. the shape of a substructure (either out of the domain, e.g. a bridge pier, or within the domain, e.g. a shipping channel),
- local bathymetry.

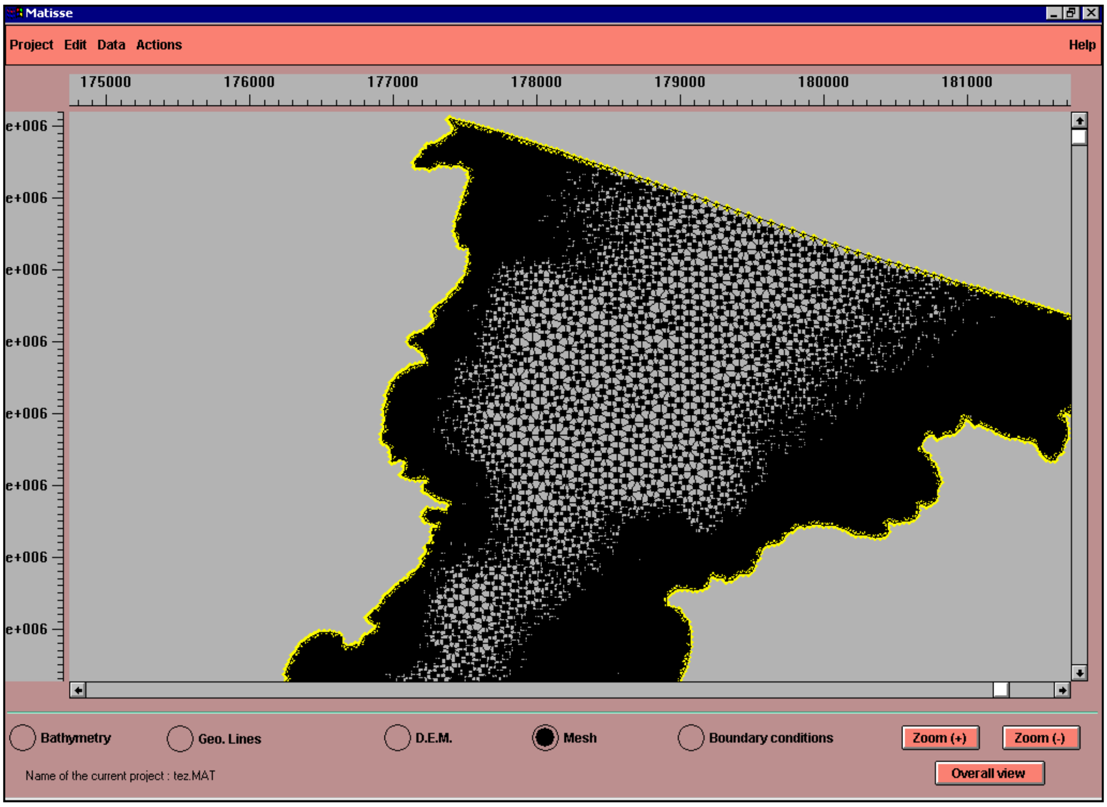

Fig. (3.3): The mesh covering the domain of the northern Bosphorus.

Mesh generation is not the only purpose of MATISSE. The latter is used as well for interactively defining the boundary conditions along the domain borders. It consists of five main sections dealing with the various operating modes:

- **Bathymetry mode:**

In all the hydrodynamic applications, bathymetry is a major item for generating a mesh, since it governs the flow. It is an essential parameter for the mesh generating algorithms. In this mode, it is possible to gain access to sources of various kinds of bathymetry data representing the field. In order to add new bathymetry data, e.g. from digitized maps, these data should be described in one of the MATISSE-readable formats, namely:

SINUSX (digitized map format).

The usual procedure of the bathymetry mode is based on three steps:

- reading new bathymetry data,
- processing (modifying) the bathymetry data,
- checking bathymetry through a graphic display.

- **Geometric lines mode:**

Once the bathymetry data are input into MATISSE, this operating mode makes it possible to define the computational domain outline (contour lines), e.g. from the bathymetry. Through this, the mesh generating algorithms will define some position limits of the points and segments in the future mesh.

The usual procedure consists of the following three steps:

- including new line data,
- processing (modifying) the geometrical lines,
- through the graphics display, checking bathymetry along the geometrical lines.

- **D.E.M mode:**

This step is essential to the operation of the mesh generating algorithms on which MATISSE is based. It is provided to prepare the density map, i.e. a basic mesh on which a list of criteria and, consequently, a desired inter-node distance are defined at each point. A criterion is a two-dimensional scalar function to be used for defining the inter-point distance. The digital terrane model (DEM) globally comprises Bathymetry-Geometric lines-Density map.

This step is the first triangulation step. The standard procedure comprises five steps:

- selecting the basic mesh of the density map,
- adding new criteria
- processing (amend or create) the criteria data,

- checking the criteria using the graphical display,
- computing the inter-node distance function.

- **Mesh mode:**

Among all the defined geometric lines, there must have been chosen the future constraint lines (a constraint line is a user-defined line serving as a support for nodes and segments of the future mesh. The segment will be linked to the line and shall not intersect it) to be used for generating the mesh. Subsequently, the generation is performed. In Fig. (3.3), a generated mesh could be seen. It is possible to return upstream and take new constraint lines into account, then assess the improvements of the resulting mesh.

Lastly, it is possible to change manually the generated mesh in order to specify some items. On completion of these changes, automatic checks are performed by MATISSE software to ensure a proper arrangement of the final mesh.

Once the checks are made, it is time to write the associated geometry file, as required in the TELEMAC-3D modeling system. This file is one of the two input files generated by MATISSE software for the computation.

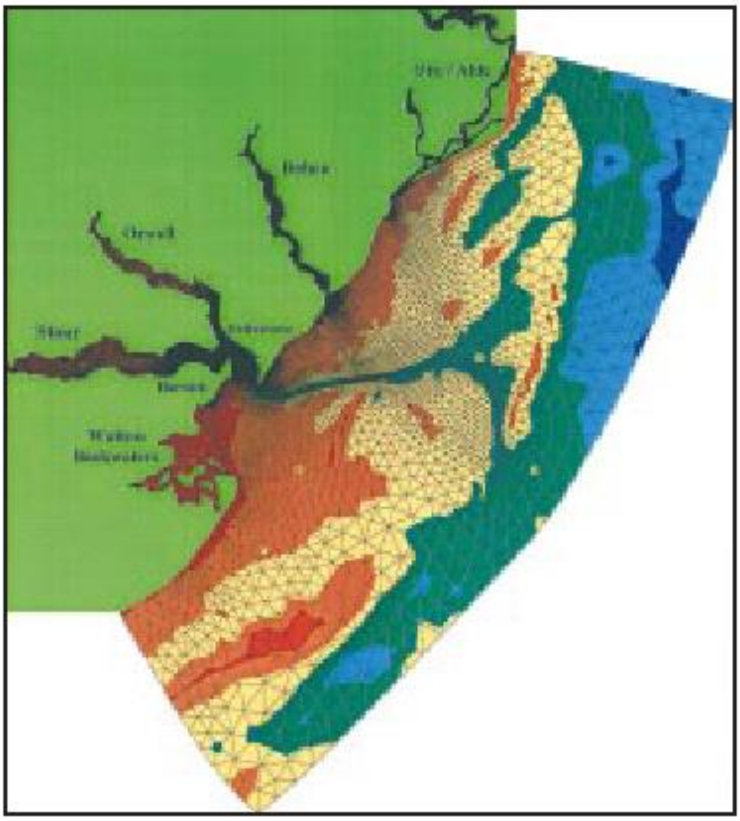

Fig. (3.4): The mesh viewed on its physical domain.

- **Boundary conditions mode:**

The ultimate step upon mesh generation through MATISSE involves defining the boundary conditions. Through this step, it is intended to define both types and values (when the latter is constant on a time basis) of the boundary conditions to be considered at the various nodes of the domain boundary. This mode will result in the generation of the CONLIM file (boundary conditions file) as required for operating the TELEMAC-3D software.

The boundary conditions are defined by two items, namely the Entities and the Groups. Entities are the boundary condition characteristics at one node. Gathers all the kinds of boundary conditions for all the variables (h, u, v, T). It consists therefore of a set of 4 pairs (integer+real), each integer ranging between 0 and 6. An entity is defined by an entity name. The possible conditions are listed in the Tab. (3.1). Groups are set of nodes belonging to the contour lines (A contour line is a geometric line making up an outside or inside boundary of the represented domain). Similarly, a group is defined by a group name. In that case, to define a boundary condition of a contour line, the groups are needed to associate with the related entities.

Tab. (3.1): Available options of the boundary conditions.

Generic name	**Color code**	**Corresponding boundary condition**
Sliding	2	Solid boundary with a sliding condition
Free	4	“Free” liquid boundary
Imposed-values	5	Imposed value liquid boundary (values for velocity)
Imposed-values	6	Imposed value liquid boundary (values for discharge)

3.2. Input and Output Files

During a computation, TELEMAC-3D uses a number of input and output files, some of which are optional. Input files include:

- the geometry file and the boundary conditions file (generated by MATISSE),
- the steering file,
- the FORTRAN file,
- the bottom topography file (optional),
- the previous computation file (optional).

Output files include:

- the 3D result file,
- the 2D result file,
- the listing printout file.

3.2.1. The Steering File

This is a text file created directly by a text editor. It represents a sort of reference sheet for the computation. It contains a set of key words that are assigned values. If a key word does not appear in this file, TELEMAC-3D assigns it the default value defined in the dictionary file. The dictionary file contains all information on the key words (French name, English name, default values, type, and keyword documentation). If such a default value has not been defined in the dictionary, the computation stops and an error message is displayed. For example, the command *TIME STEP = 10* indicates that the computational time step has a value of 10 seconds. An example of the steering file that is used in the computation of the Bosphorus hydrodynamics is given in Appendix 1.

3.2.2. The Geometry File

This is the file that is created by the MATISSE mesh generator. This file contains all the information concerning the 2D mesh (see chapter 3.1). It includes the number of mesh points (variable NPOIN2), the number of elements (variable NELEM2), the number of vertices per element (variable NDP), tables X and Y containing the coordinates of all the points.

3.2.3. The Boundary Conditions File

This is the second file that is created by the MATISSE mesh generator. This file can be modified by a text editor. Each line of this file is devoted to a point on the 2D mesh boundary. The numbering of the boundary points is the same as that of the file lines. It describes firstly the contour of the domain, in the trigonometric direction, starting from the bottom left-hand point (X + Y minimum), and then the islands, moving clockwise.

The lines of this file represent the associated entity of the elements belonging to the groups. The points of the 3D mesh that are reproduced from the 2D mesh by prescribing the number of the horizontal levels (from surface to bottom) in the steering file also have the same entity and hence the same boundary conditions. A part of the boundary conditions file that is used in the simulation is given in Appendix 2.

3.2.4. The Fortran File

The FORTRAN file contains routines that are specially developed for the calculation and a number of subroutines (called "user subroutines") of TELEMAC-3D in FORTRAN77 format that could need to modify for different cases. These user subroutines, drawn from the various libraries used by TELEMAC-3D, are given in the list in Appendix 3.

The Fortran File contains at least the main TELEMAC-3D program to be run. The role of this main program is only to specify the language used for writing the messages (English or French) and for specifying the memory space by indicating the size of the A (real) and I (integer) tables. If the size specified is too small, the TELEMAC-3D run is interrupted and the software prints out the minimum value to be specified in the main program. Otherwise, it is needed to recover the exact size used by the program, so that it can then accurately size the memory space and thus save central memory space. An example of a Fortran file is given in Appendix 4.

3.2.5. 3D Result File

This is the file in which TELEMAC-3D stores information during the calculation. It contains all information concerning the mesh geometry, and the names of the stored variables. It then contains the time for each time step, and the values of the different variables for each mesh point.

The 3D result file is then used by RUBENS software as an input to visualize these result data via graphic format.

4. MODELING OF THE BOSPHORUS

The model of the Bosphorus was constituted with starting the mesh generation covering the computational domain. The mesh was generated by the MATISSE software that is a part of the TELEMAC system as stated before. Here, the steps of the mesh generation following by defining the boundary conditions and also preparing the steering and the FORTRAN files are explained.

4.1. Mesh Generation

The most required item for the reliability of the simulation results is an accurate bathymetry map representing the physical features e.g. the coastline and the bottom topography of the Bosphorus Strait. For this reason, the digital bathymetry map of the region [Fig. (4.1)] is provided from the Department of Navigation, Hydrography and Oceanography of the Turkish Navy (DNHO).

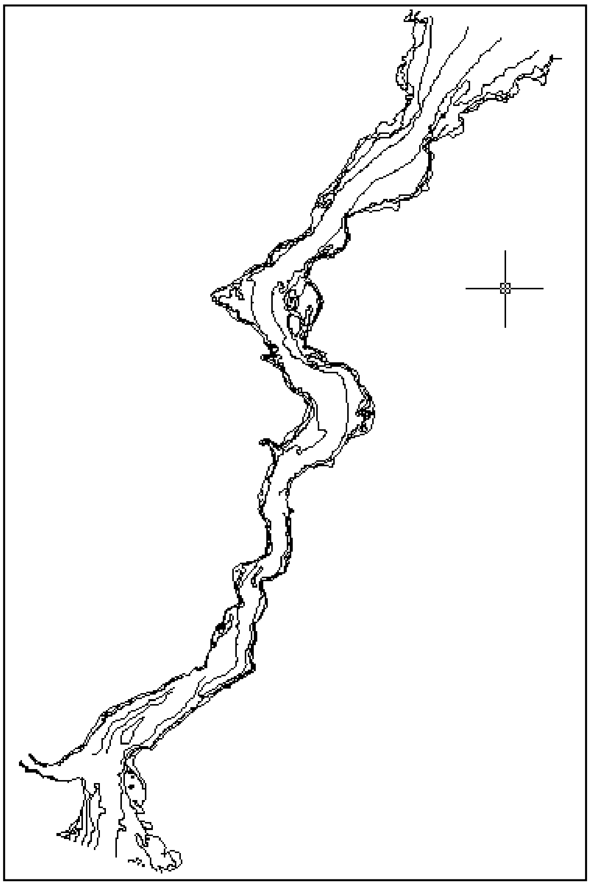

Fig. (4.1): The digital bathymetry map of the Bosphorus Strait.

As stated before the format of the data that MATISSE requires is in the Sinus-X format. For this reason, the initial digital map of the dwg format was converted to the Sinus-X by the SINUSX program. By this module, the digital map was divided into two parts, one consisting of only the coastlines and the other only the bathymetry nodes. At that moment, the height of the coastline on both sides of the Bosphorus Strait was taken as 2m with an assumption.

In Fig. (4.2a-b), the input digital map of Sinus-X format into the bathymetry mode of MATISSE is presented. As stated before in the bathymetry mode, there are two kinds of nodes forming the whole domain. The nodes in the blue color indicate the bottom topography and hence the water depths, and the black nodes form the coastline as they connected sequent to each other. Here, the coastline nodes have the depth of –2m. The plane of the zero value of depth forms the reference level and so the bathymetry nodes have the depths of negative values. The nodes of –100m, have the smallest value and represent the deepest parts of the Bosphorus Strait.

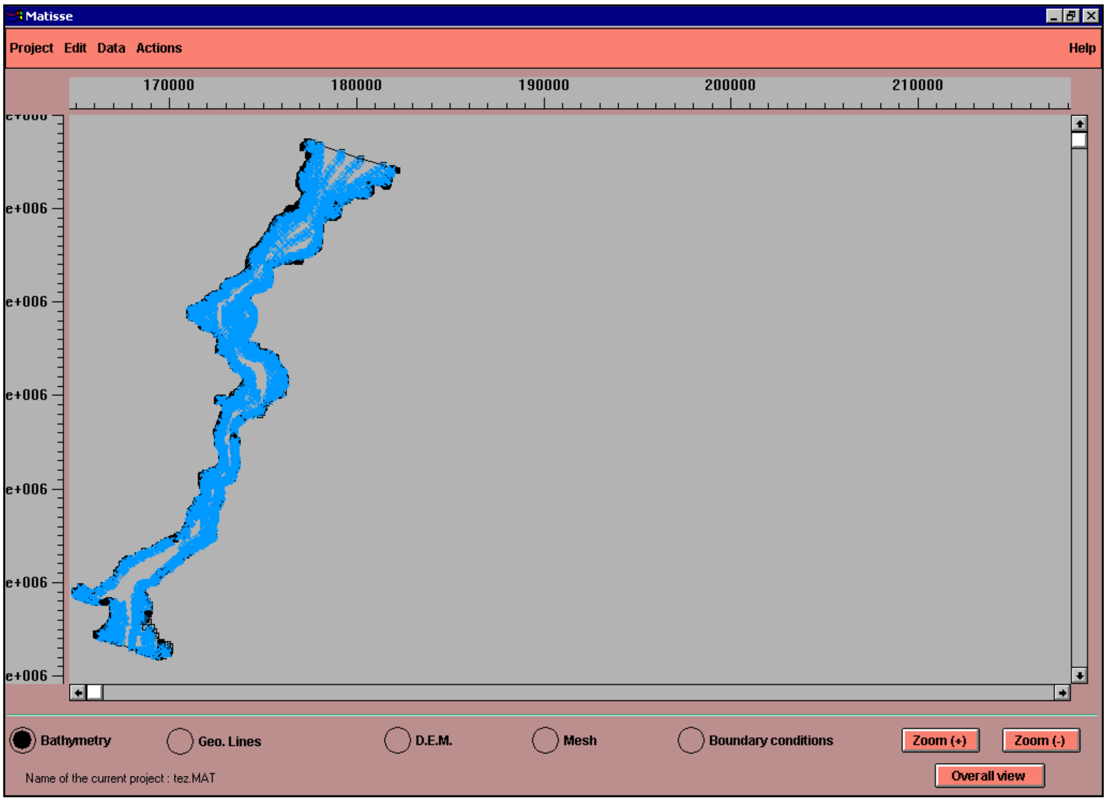

Fig. (4.2a): The Sinus-X format of the digital map of Bosphorus input into the bathymetry mode.

All the points in the domain are placed according the global coordinate system. The x and y axes are on the positive coordinate plane: The x-axis is oriented rightwards and the y-axis is upwards. In Fig. (4.2b), the coordinate values of a node with the bottom topography information (bathymetry) are presented.

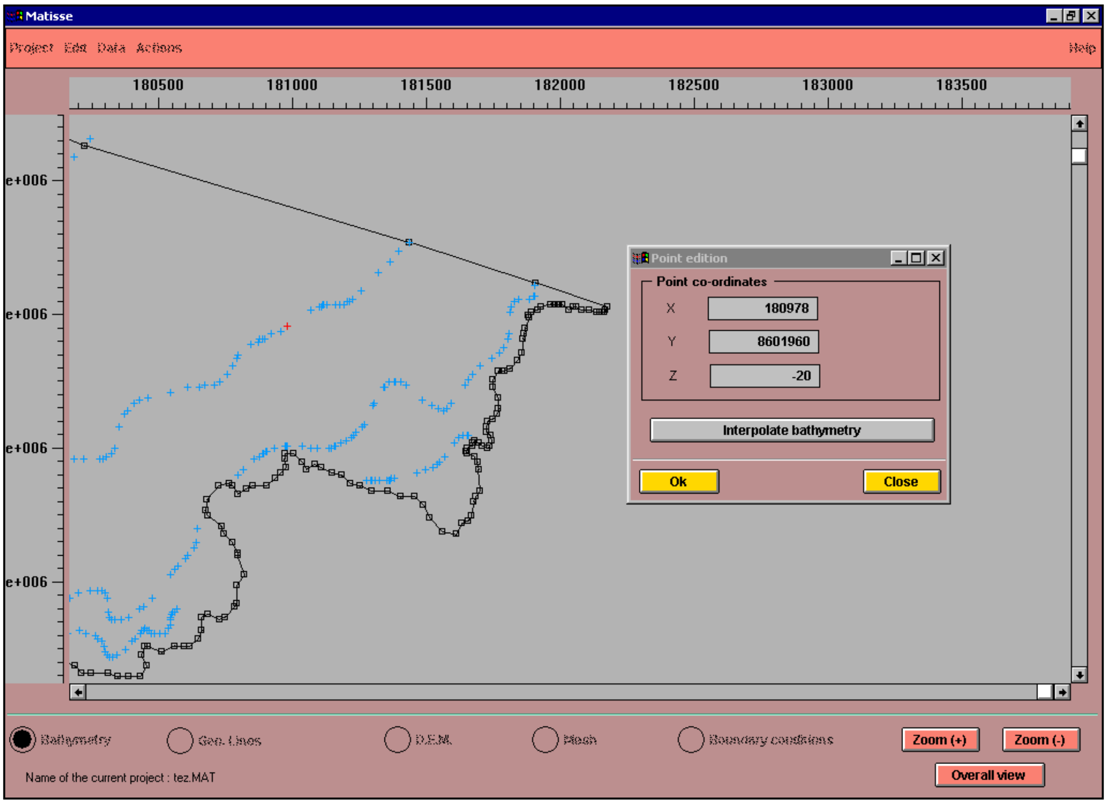

Fig. (4.2b): The nodes representing the bottom topography and the coastline.

At the next stage, the domain, that the Bosphorus flow would be examined through, was restricted by the created lines at the exit regions of the strait in the geometric lines mode as in Fig. (4.3). Consequently, the domain was formed, including the northern sill at the Black Sea exit and the constriction region located within the southern end of the strait.

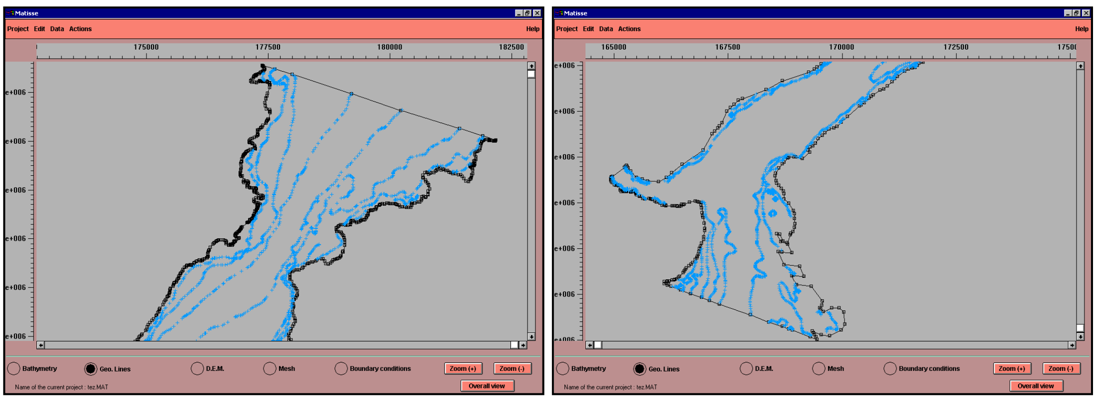

Fig. (4.3): The exit regions of the Bosphorus Strait.

Near the southern exit region of the strait, the Golden Horn was also restricted with allowing an efficient indentation. The geometric line would then act like a coastline at this part.

There is a very important point in terms of finite element method regarding to the mesh generation, is that, the intensity of the created mesh adjacent to the coastlines or to the places showing large variations of bottom topography, has to be more dense that of the mesh created on areas showing more uniform topography. For this purpose, the mesh elements on the coastal zones of the Bosphorus were created more dense than the ones in the middle parts. In the DEM mode, two criterions were created covering the coastal and the middle zone nodes, respectively. In Fig. (4.4), a part of the selected nodes of the coastal zone belonging to the criterion that have a value of 35m for the future mesh elements can be seen. The other criterion that covers the middle zone nodes has a value of 100m.

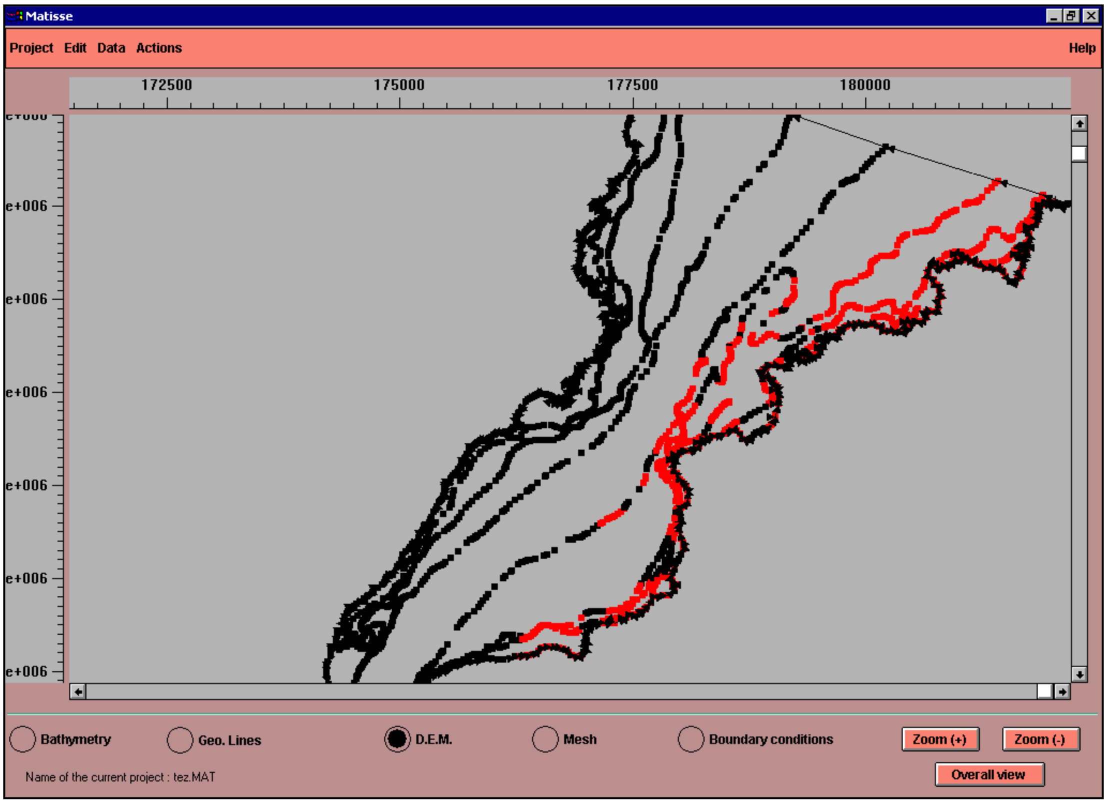

Fig. (4.4): The selection of the nodes of coastal zone for generating the criterion of 35m.

Generating this kind of non-uniform mesh results with a more accurate representation of the bottom topography of the steep slope in the coastal zone along the Bosphorus Strait. In this way, the total computation time of the simulation is also reduced.

The mesh, generated by considering the above criterions is presented in Fig. (4.5a-b). It is consisting of 42692 nodes and 82705 elements. This is the most detailed mesh that could be processed by the MATISSE software for the model without stopping the interpolation process of the bathymetry.

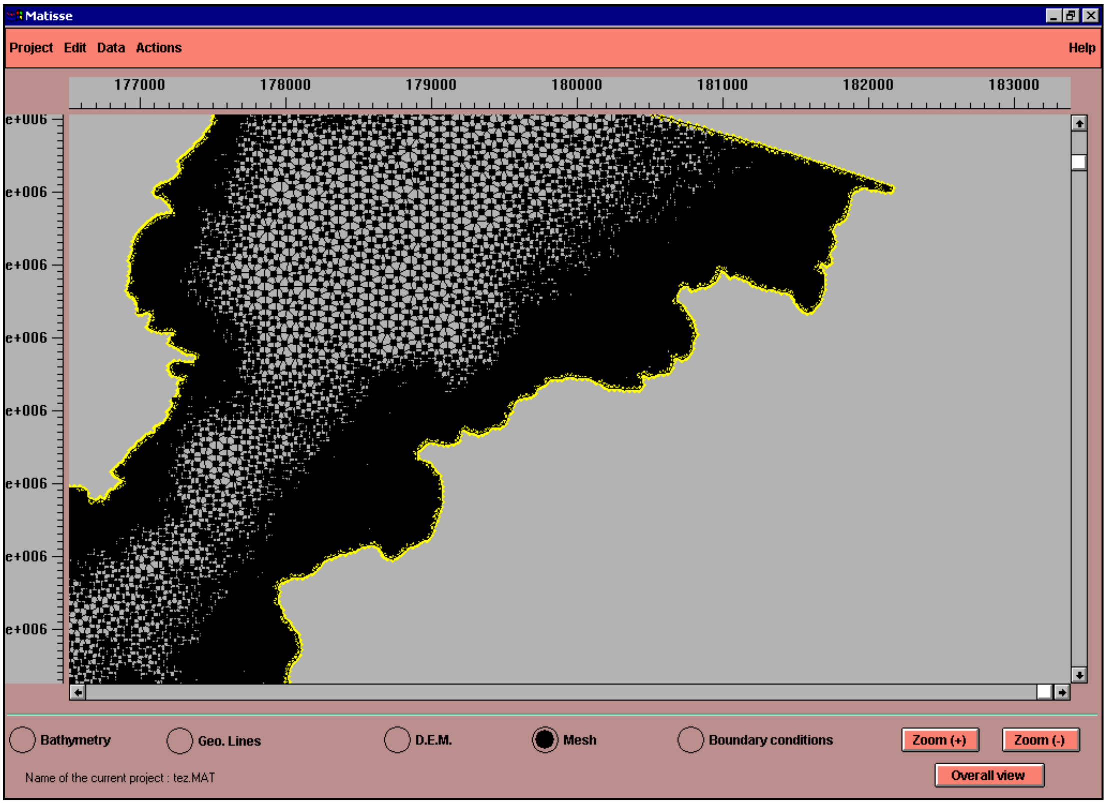

Fig. (4.5a): The created mesh over the northern exit of the Bosphorus Strait.

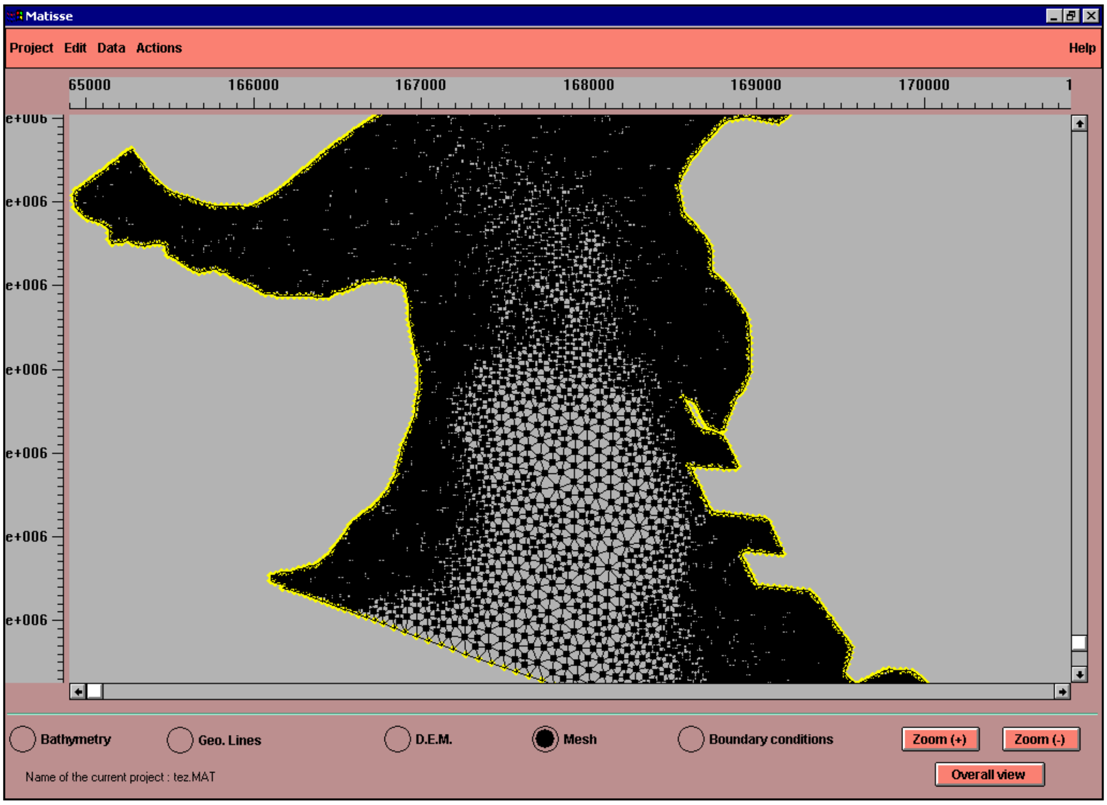

Fig. (4.5b): The created mesh over the southern exit of the Bosphorus Strait.

As a result of interpolating the bathymetry values of the input digital map over the whole domain, i.e. generating the mesh, the geometry file was created by MATISSE for the TELEMAC-3D code. The continuous bottom topography of the Bosphorus Strait is displayed via graphics of colored surfaces as in Fig. (4.6). These graphics were obtained through RUBENS software that is the part of the TELEMAC system.

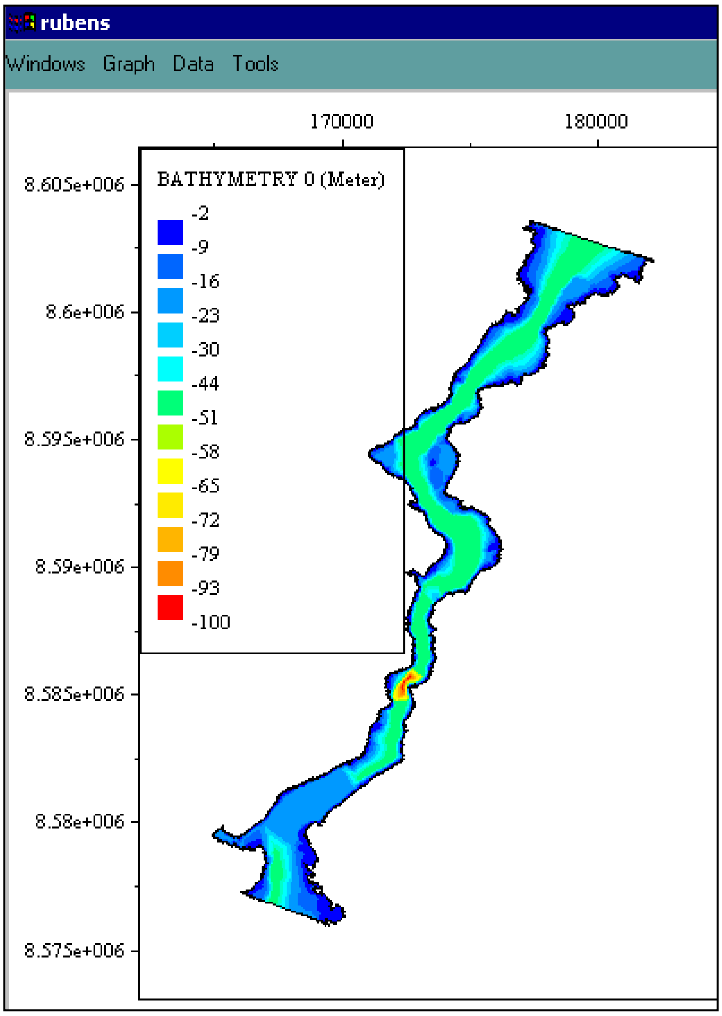

Fig. (4.6): Colored surface of bathymetry after the mesh generation.

As it is presented in Fig. (4.6), the deepest part of the strait has the value of –100m at Kandilli-Bebek section. The channel has a mean depth of 50m, goes through the strait with shallower areas covering the bays. The narrowest width occurs at about 12km north of the southern end. The northern exit of the Bosphorus to the Black Sea has a canyon type topography that swerving to the northwest.

In the following section, the boundary conditions that would be used for the simulation is explained. For defining the boundary conditions, the data of the flow conditions received from recent surveys are considered and also the information of inputting these data to the model is introduced.

4.2. The Boundary Conditions

One of the most important parts of constituting the simulation of the Bosphorus was the defining the boundary conditions of the domain. The type of boundary conditions of the domain was defined in the boundary conditions mode of MATISSE software. There are four types of boundary conditions associated with color codes that TELEMAC-3D use as stated before in Chapter3.

The southern exit of the Bosphorus to the Marmara Sea was defined as the "prescribed discharge" type of liquid boundary and has the "6-4-4" associated color code. The discharge values used on the boundary were presented in the following section.

The northern exit of the Bosphorus to the Black Sea was defined as the "free water depth and velocities" type of liquid boundary has the "4-4-4" associated color code. In addition to these, the coastlines on both sides of the strait were defined as the "solid wall" type of boundary.

These color codes were defined by creating the entities in the boundary conditions mode. Consequently, these entities were associated with the related groups of the boundary nodes as in Fig. (4.7) and the boundary conditions file was also created for the TELEMAC-3D code.

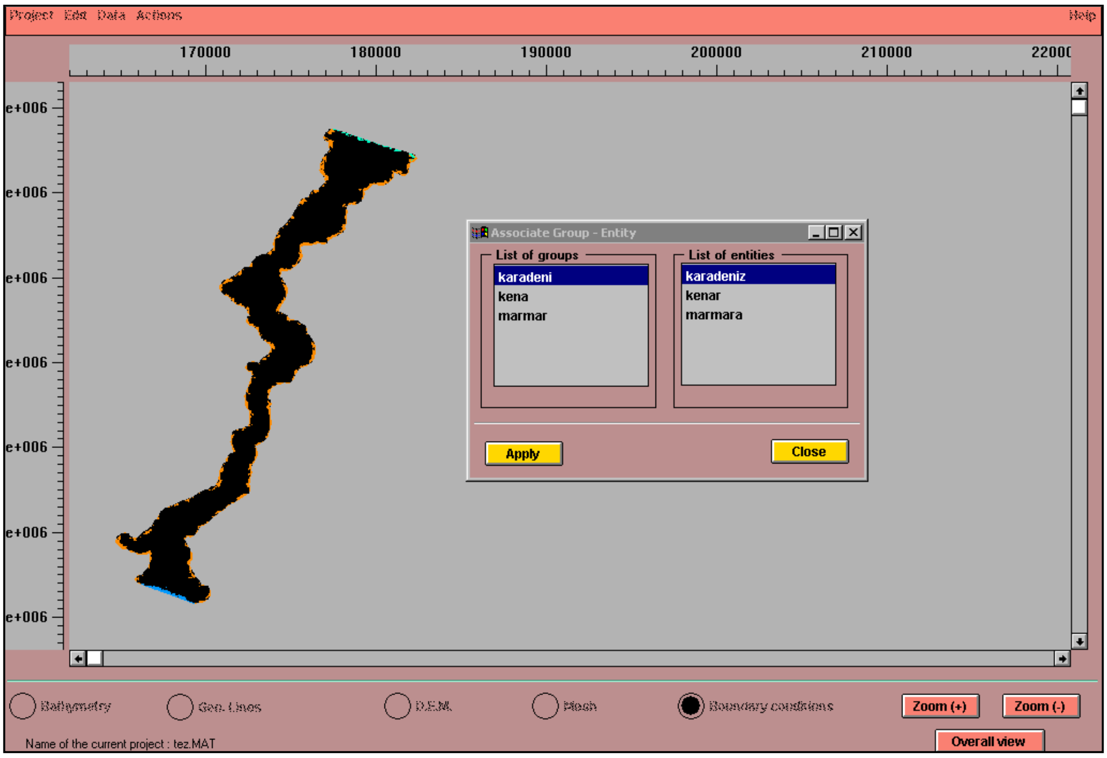

Fig. (4.7): Association the groups with the entities.

4.2.1. The Marmara Sea Exit

The prescribed discharge type of the liquid boundary forming the Marmara Sea exit was defined by considering the flow conditions at the region. Trough the results of the conducted surveys, this region is characterized by intense mixing of the bottom waters into the upper layer, a sharp upward tilt of the interface and the intensification of the upper layer currents. Özsoy et al. (1986) showed that this vertical mixing in the region results in a total increase of about 2-3ppt in the upper layer salinity between the two ends of the Bosphorus. The salinity of the northerly flowing bottom layer waters decreases accordingly by about 2-3ppt. The interfacial zone becomes much broader as compared with further upstream and has a thickness of 20-30m. Consequently, the surface layer flow eventually exits from the southern exit in the form of a thin and narrow turbulent buoyant jet and its thickness was taken as 15m below the surface in the simulation as the boundary condition. So, the depths of the bottom layer of the Mediterranean waters flowing into the strait had the values below –15m.

Defining the discharge values of the two layers on this liquid boundary was a delicate problem because the flows through the Turkish Strait System are subject to a great degree of transient variability, depending on the atmospheric factors and the water budget. Complex relationships exist between the exchange flows, sea level variations, net water budgets and atmospheric pressure variations in the adjacent basins, and are not so easily understood within the full range of time scales.

The hydrological regimes of adjacent basins establish the long-term fluxes across the Bosphorus Strait and determine the properties of waters in transit. In the Black Sea, the excess of precipitation ($P \cong 300km^3/yr$) and runoff ($R \cong 350km^3/yr$) versus evaporation ($E \cong 350km^3/yr$) is balanced by a net outflow ($Q_b \cong 300km^3/yr$) through the Bosphorus (Ünlüata et al, 1990).

A summary of ADCP based flux measurements (in the course of studies of mixing and dispersion of waste waters from the city of Istanbul) conducted by Özsoy et al. (1994, 1996) in the Bosphorus is given in Fig. (4.8) and on a seasonal basis in Fig. (4.9).

The long-term average mass budget requires $Q_1/Q_2 = S_2/S_1 \cong 2$, where Q_1, S_1 and Q_2, S_2 are the fluxes and salinities respectively in the upper (outflowing waters of the Black Sea) and lower (incoming waters of the Mediterranean Sea) layers at the Bosphorus (Özsoy et al, 1998).

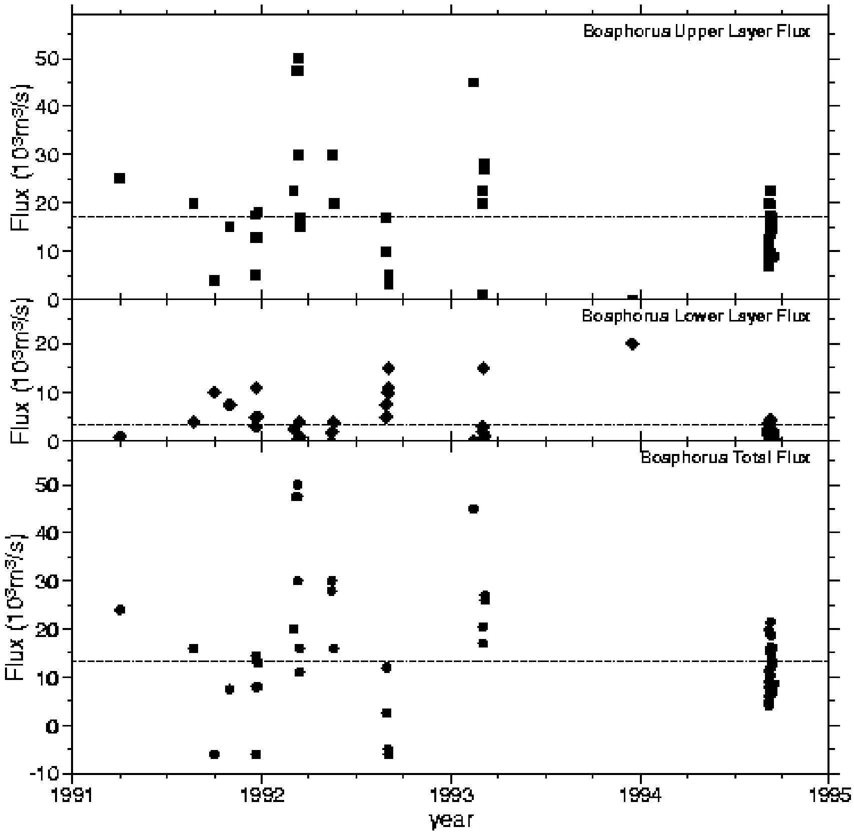

Fig. (4.8): ADCP measurements of upper, lower layer and total volume fluxes in the Bosphorus, during 1991-1994. Dotted lines represent mean values.

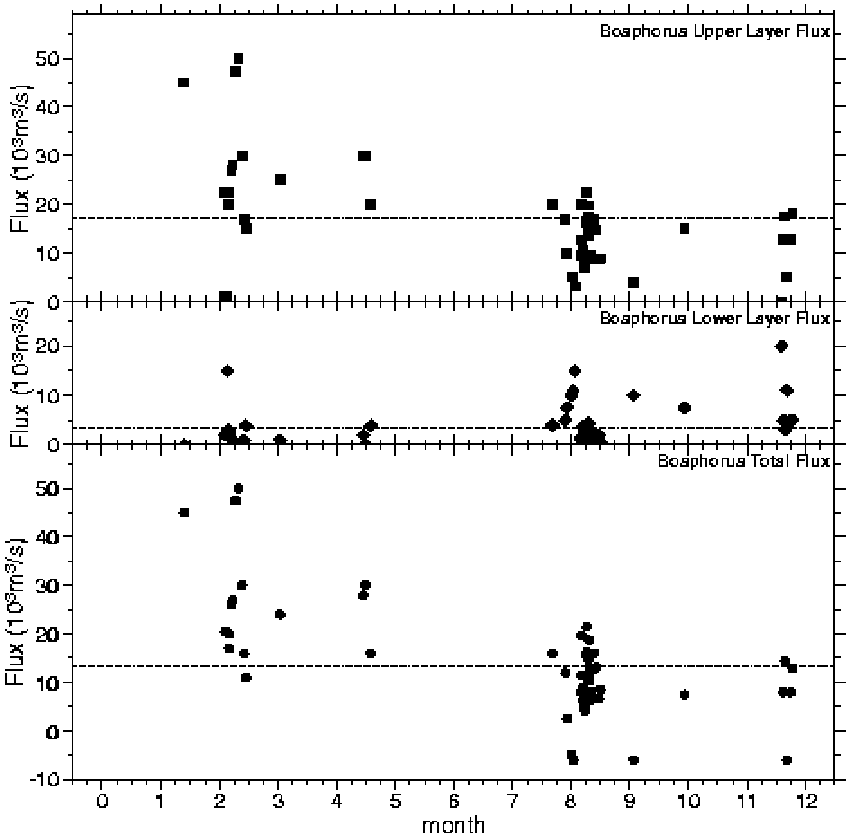

Fig. (4.9): ADCP measurements of upper, lower layer and total volume fluxes in the Bosphorus, plotted on a seasonal basis. Dotted lines represent mean values.

The fluxes estimated from the mean value of these measurements are $Q_1 \cong 540km^3/yr = 17,000m^3/sec$ in the upper layer, and $Q_2 \cong 115km^3/yr = 3,600m^3/sec$ in the lower layer. In addition, Özsoy et al. (1998) notes that many of the values in the Fig. (4.8) and Fig. (4.9) representing blocked or nearly blocked conditions are included in the average. Because of this situation, these values need some corrections for the mean fluxes.

Assuming the cross-section of the channel into which the Mediterranean water is confined to be $6400m^2$, Yüce (1996) estimates the range of the bottom layer flow into the strait as $2400\text{-}4050m^3/sec$ by taking into account the observed minimum and maximum current values of his study.

Considering long-term average mass budgets along the strait and the above values, the discharge of the upper layer and the lower layer was taken as $350km^3/yr \cong 11000m^3/sec$ and $175km^3/yr \cong 5500m^3/sec$, respectively. These values were introduced to the TELEMAC-3D code by the related subroutines in the FORTRAN file. Also, these discharges would have the relevant salinity values that are given in the following part.

4.3. Initial Conditions

Another important phenomenon acting on the flow regime along the Bosphorus Strait is the difference of salinities between the upper and lower layers. In the long term, mass balance requires a ratio of ~ ½ between the salinities of the outflowing waters of the Black Sea and the incoming waters of the Mediterranean Sea at the Bosphorus (Ünlüata et al, 1990).

With the defined boundary conditions and the discharge values, the initial conditions of the water in the strait were programmed in the FORTRAN file for an accurate run of the simulation.

At the start of the computation ($t = 0$), the water in the strait was at rest to begin with. For generating the two-way flow along the strait, the Bosphorus Strait was separated into two parts longitudinally having different salinity values. The plane that separated the parts from each other began from the depth of –40m at the Black Sea exit and finished at the depth of –15m at the Marmara Sea exit. According to the observed values of the salinities at the two regions that discussed in Chapter2, the upper part waters had the salinity value of %1,6 and the lower part waters had the salinity value of %3,8. Under these circumstances, the simulation resulted by 1440 iterations within 3½ hours.

5. RESULTS AND DISCUSSIONS

The simulation results are displayed either on the horizontal and vertical cross-sections taken along the strait. These cross-sections were taken by the POSTEL-3D software. The horizontal cross sections could be taken at different water depths with the utility of the 3-D mesh created by the TELEMAC code (Fig. 5.1). These results represent the flow conditions of the last time step of the computation. The total number of iteration of the simulation was 1440 and the calculation time was about 3½ hours.

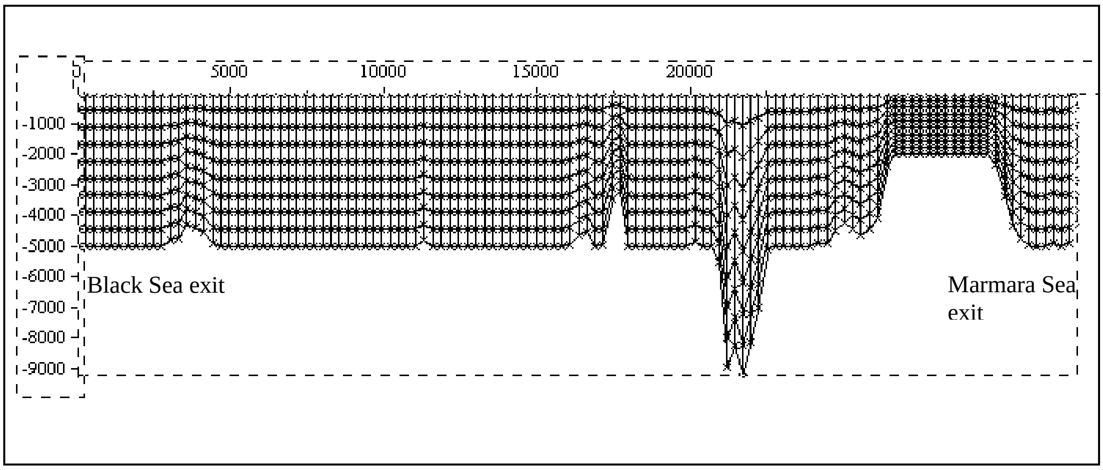

Fig. (5.1): The vertical cross-section of the 3-D mesh.

The main notations that the graphics use are that, the positive x-axis goes through right and the positive y-axis goes through up on the paper plain. There are three horizontal planes representing the results of the flow conditions at the –8m, -26 and –40m waters depths in the strait. The vertical cross-section was taken along the Bosphorus beginning from the southern exit (Marmara Sea) finishing at the northern boundary exit (Black Sea).

In Fig. (5.2), the resultant velocity vectors of the simulation at the water depth of –8m (8m below the surface) can be seen along the strait. As it can be seen in the figure, the larger velocities of the currents follow the main channel of the Bosphorus and are affected by its topography. The white parts indicate the nonexistence of the water because those parts are above the level of –8m. It can also be seen that the currents speeds are increasing at the narrow parts of the strait and especially in Bebek-Kandilli section the speed is reaching up to 1,40m/sec. The lower layer flow of the Mediterranean water is presented in Appendix 5.

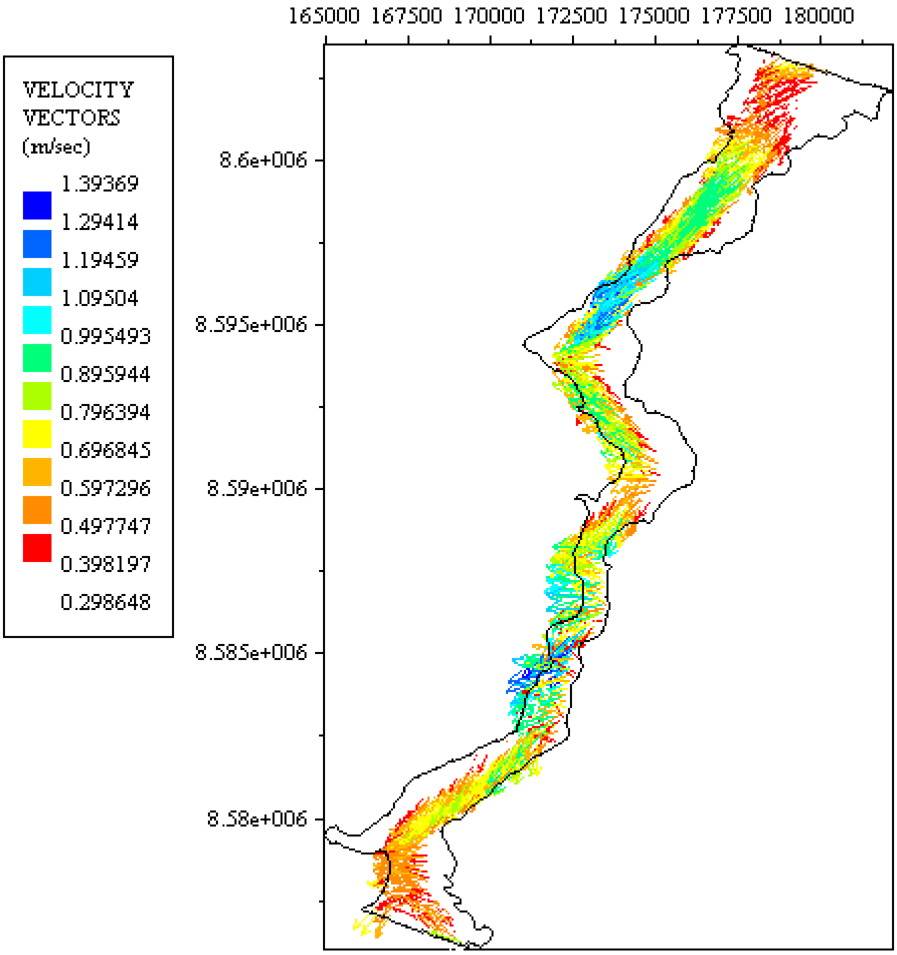

Fig. (5.2): Calculated velocity vectors of the surface (Black Sea) waters.

Özsoy et al. (2002) conducted a series of measurements in the Bosphorus Strait using ADCP and CTD profiling. Their intensive experiments were carried out during 3-6 September 1998, 4-22 March 1999 and 22 July-3 August 1999 [Fig (5.3)]. They obtained surface currents shown in Fig. (5.4a-b). These values show similarity to the simulation results for the relative speed changes of the surface layer along the strait.

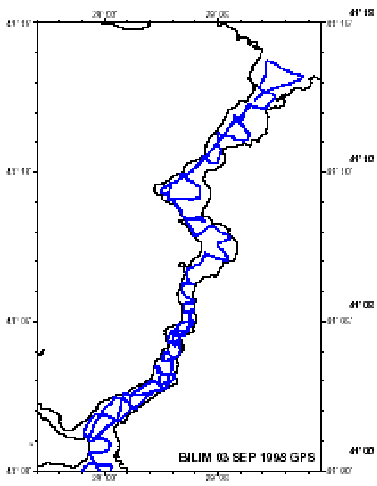

Fig. (5.3): GPS positions of the ship collecting data along the Bosphorus.

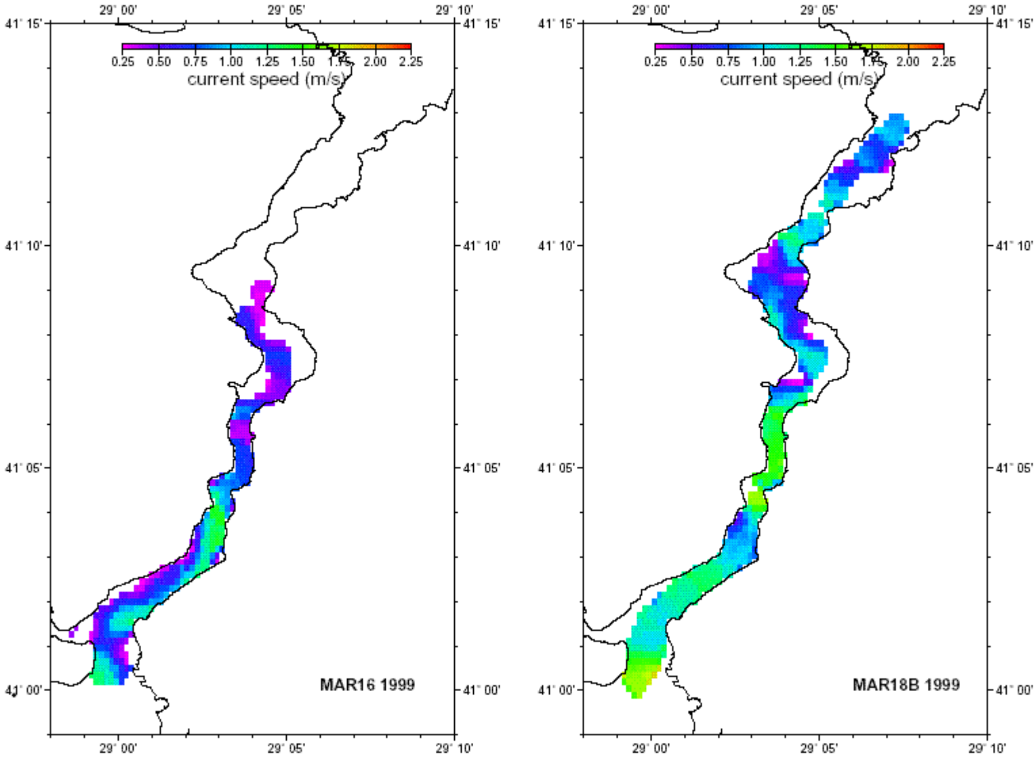

Fig. (5.4a): Interpolated speed of surface currents from continuous ADCP measurements.

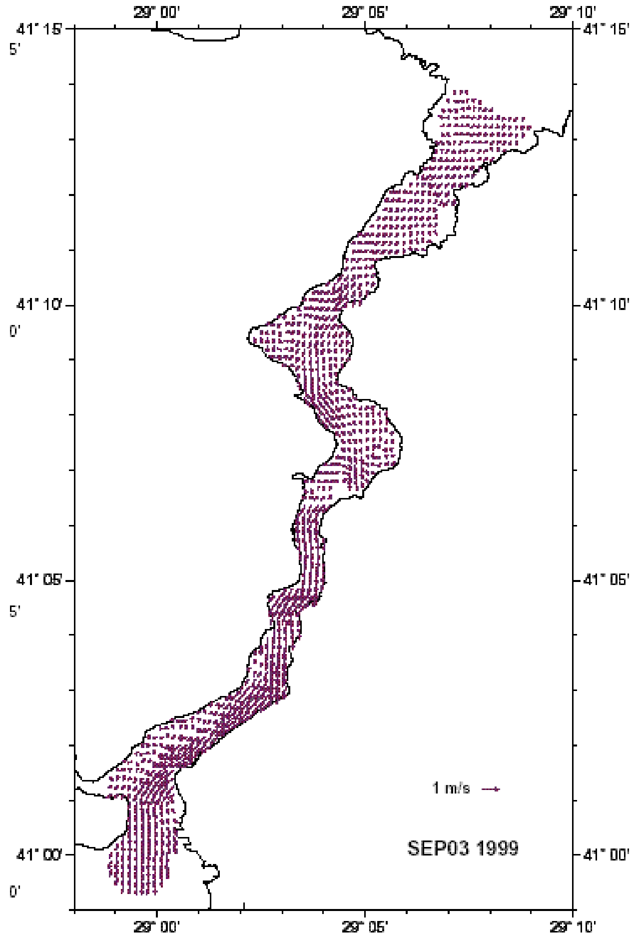

Fig. (5.4b): Interpolated speed of surface currents from continuous ADCP measurements on September 1999.

The hydrodynamic simulation results represent successfully the topography effects on the surface flow nearby the Marmara exit. Fig. (5.5) represents the surface currents intensified in the narrows in southern Bosphorus. The flow first follows the deep channel on the eastern side, and then crosses to the western side following the main channel, forming a jet near the exit to the Sea of Marmara.

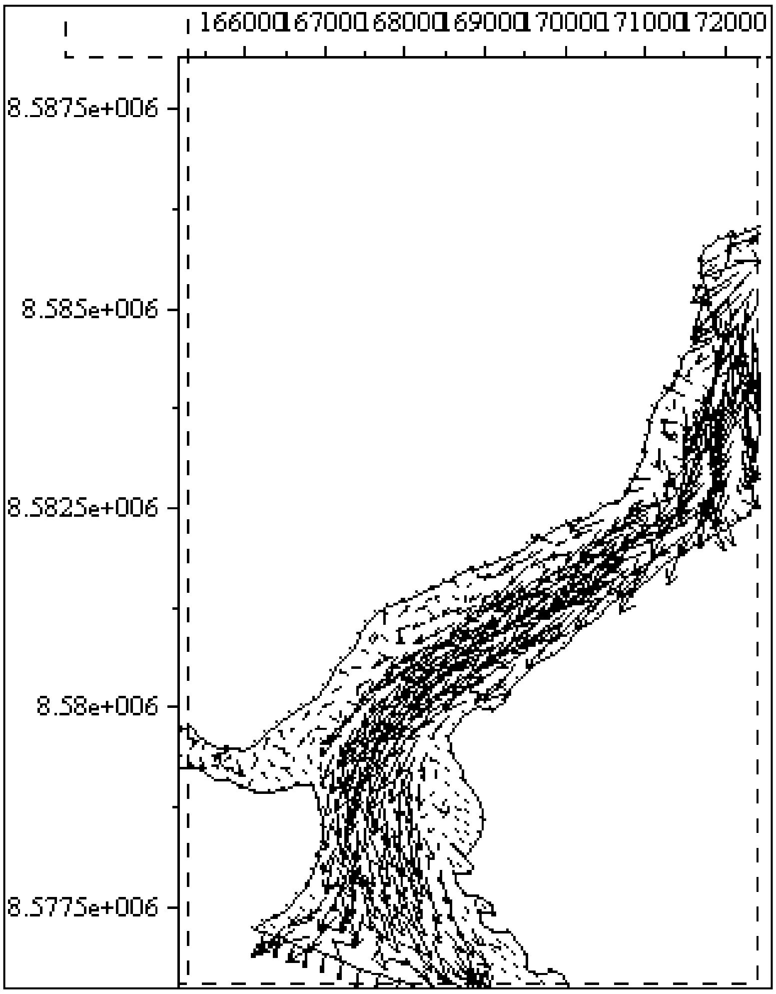

Fig. (5.5): The exit region of the Bosphorus to the Sea of Marmara.

The simulation results also prove that the Bosphorus currents have fine features that depend on coastal shape on its banks, revealing eddies and reversing currents in various of its embayments, as well as turbulent meandering of the main current. Fig. (5.6) represents the vortexes forming in the bays of the Bosphorus.

Fig. (5.7) represents the y-axis component of the vectors of the Black Sea currents along the strait at the depth of –8m. In this colored surface figure of the velocities, it is clearly seen that, the y-axis components of the velocities have the positive values (+y) in the embayed parts of the coastline because of the reversed currents. These currents have the opposite direction that the main flow of the Black Sea has.

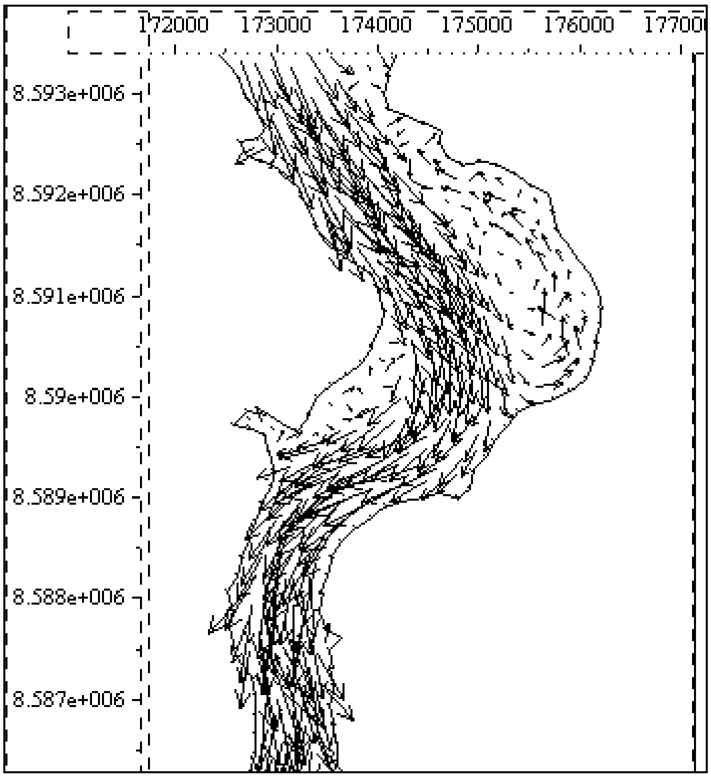

Fig. (5.6): The vortex forms of the surface waters in the Beykoz section.

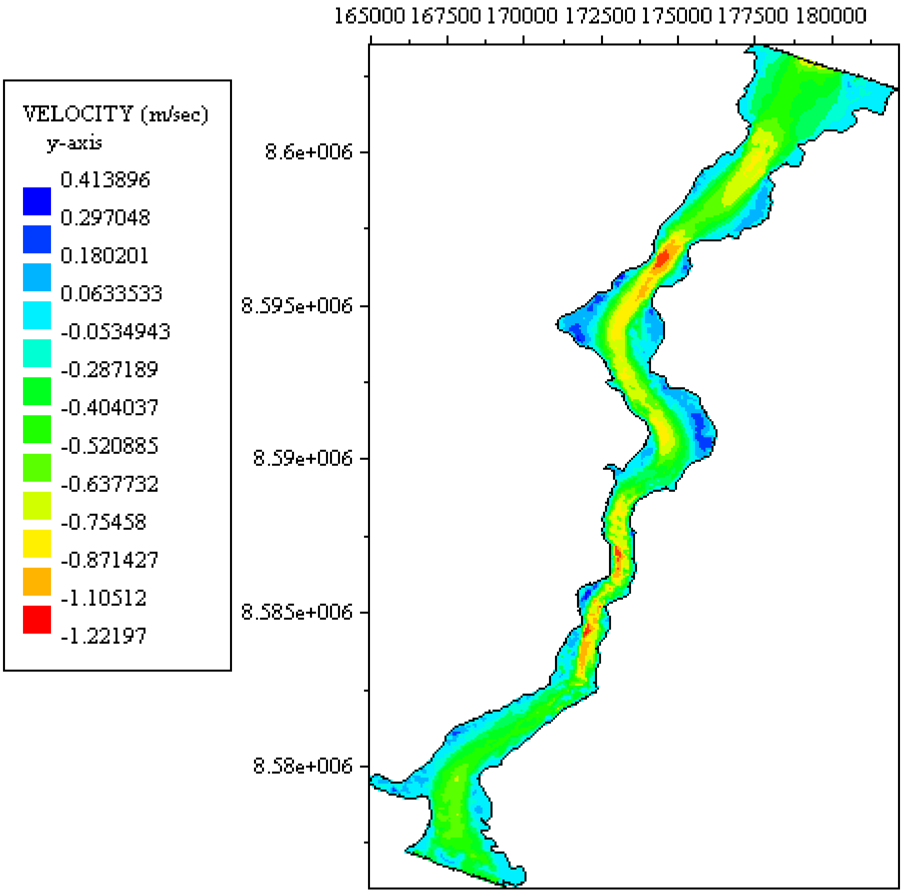

Fig. (5.7): The colored surface of the Black Sea currents on the y-axis.

Fig. (5.8) represents the salinity interface formed along the Bosphorus at the end of the simulation. It is clearly seen that the dense waters of the Mediterranean Sea are passing through the strait and reaches to the Black Sea exit. Consequently, the value of the used net barotropic flow allows the Mediterranean water to pass the strait without a blockage event.

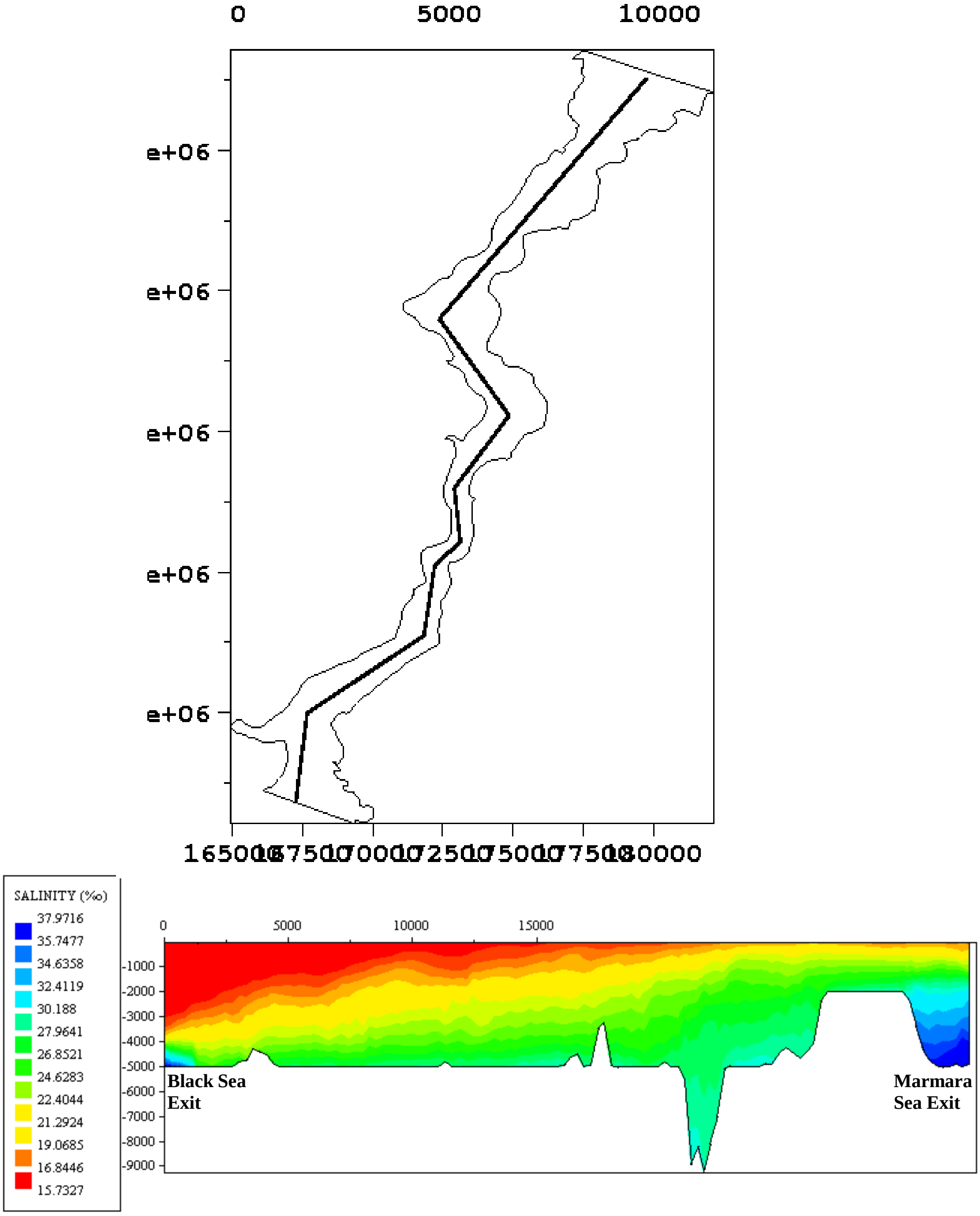

Fig. (5.8): The salinity transect taken along the Bosphorus.

As it can be seen from the above figure, at the northern half of the strait, the interface between the surface (red zone with lower salinity) and bottom waters (blue zone with higher salinity) is sharp having an average thickness of 10m. It extends with a mild slope through the Marmara exit. It is clearly seen that the low salinity waters (Black Sea origin) that forms the surface layer flow eventually exits from the southern entrance in the form of a thin jet. The simulation results successfully represent the situation of the interface observed during the field measurements using AMP [Fig. (5.9)].

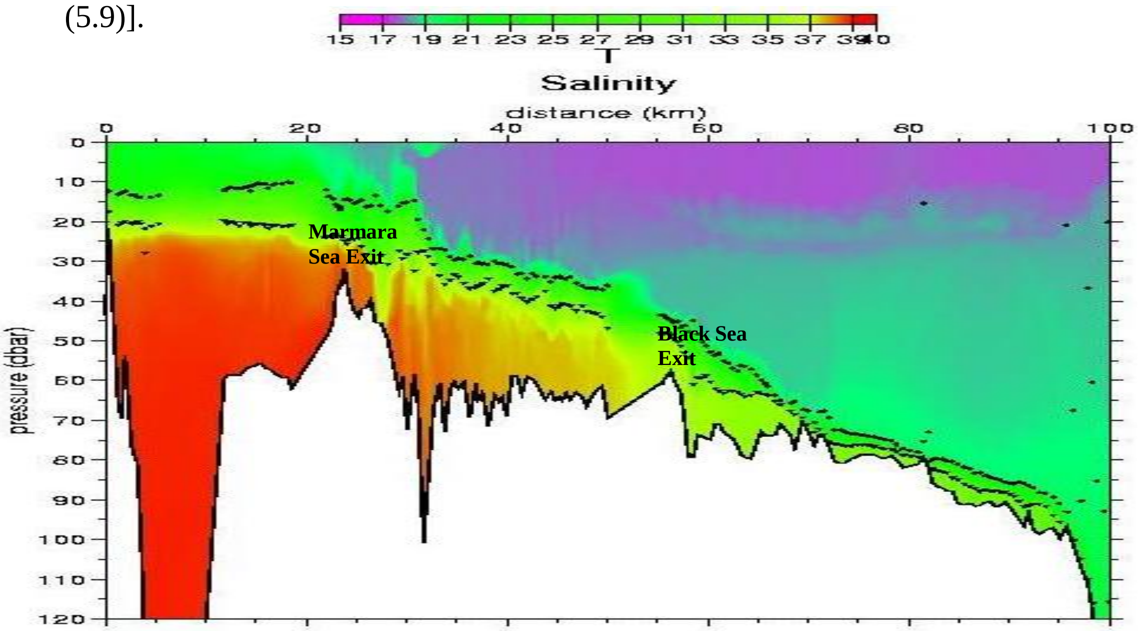

Fig. (5.9): Field measurements during 13-19 September 1994 (Özsoy et al. 2000a).

Through the vertical cross-section of the Bosphorus, the hydrodynamic simulation results show the computed distributions of layer-average salinities. In addition, it gives an idea of how the mixing and stratification characteristics along the strait may be influenced by the internal hydraulic adjustment of the exchange flow. Fig. (5.10) supports the common idea that supposes the largest changes in the transports and salinities are to occur in regions of the supercritical flow associated with the hydraulic controls. In Fig. (5.10), the most drastic changes in the transports and salinities take place in the constricted region and at the southern exit region where the channel expands abruptly to the Marmara Sea. The salinity of the surface flow increases and reaches the values of 24-25 ppt at the region. Consequently, the upper layer salinity prescribed as 16 ppt at the Black Sea termination of the strait increases typically to 23-25 ppt at the southern exit region. On the other hand Fig. (5.11) shows that the lower layer salinity of 38 ppt at the Marmara end of the strait may decrease down to 28 ppt at the northern exit region. This proves that the Mediterranean effluent is diluted to a considerable extent before it joins into the western Black Sea.

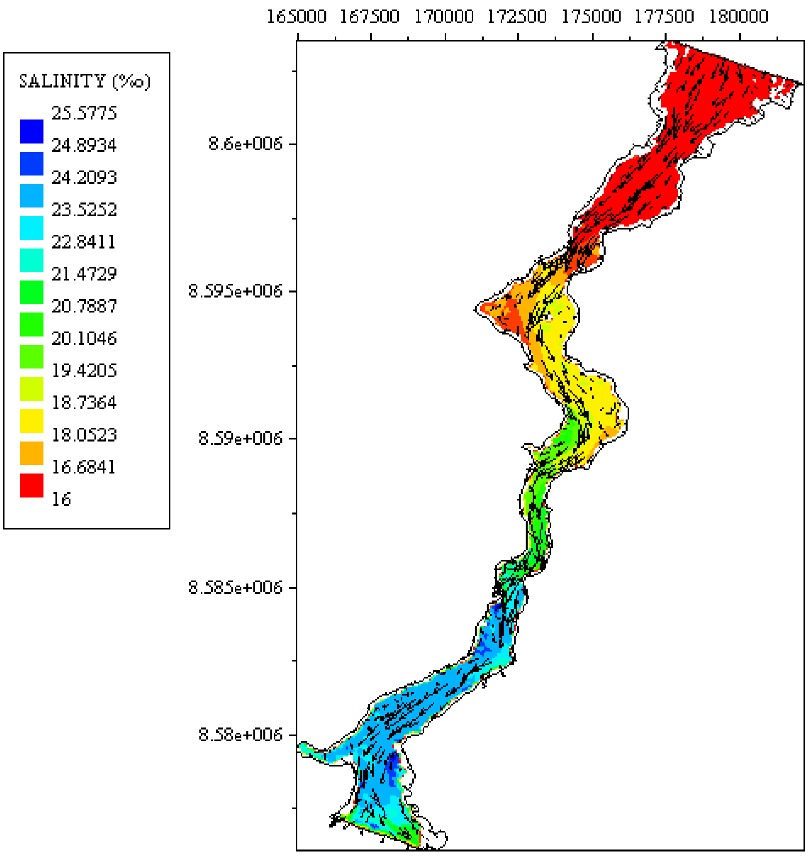

Fig. (5.10): Increase of the upper layer salinity through the Bosphorus Strait.

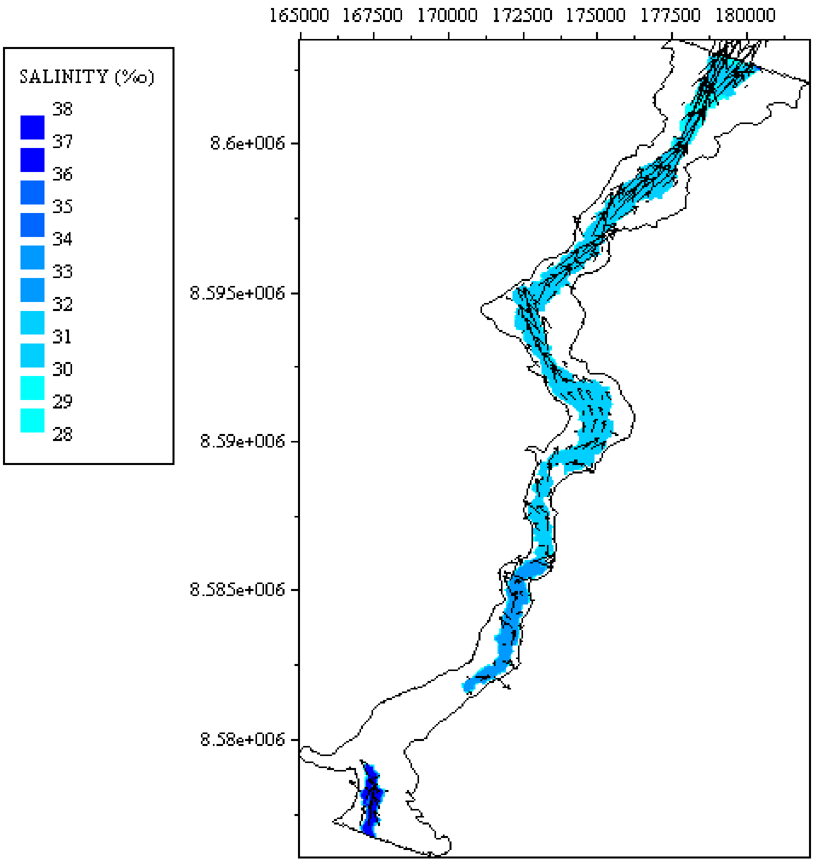

Fig. (5.11): Decrease of the lower layer salinity through the Bosphorus Strait.

These results are also compatible with the field data represented by Özsoy et al. (2000b) in Fig. (5.12). The simulation result representing the interface depth variation and vertical mixing can be seen in Appendix 6.

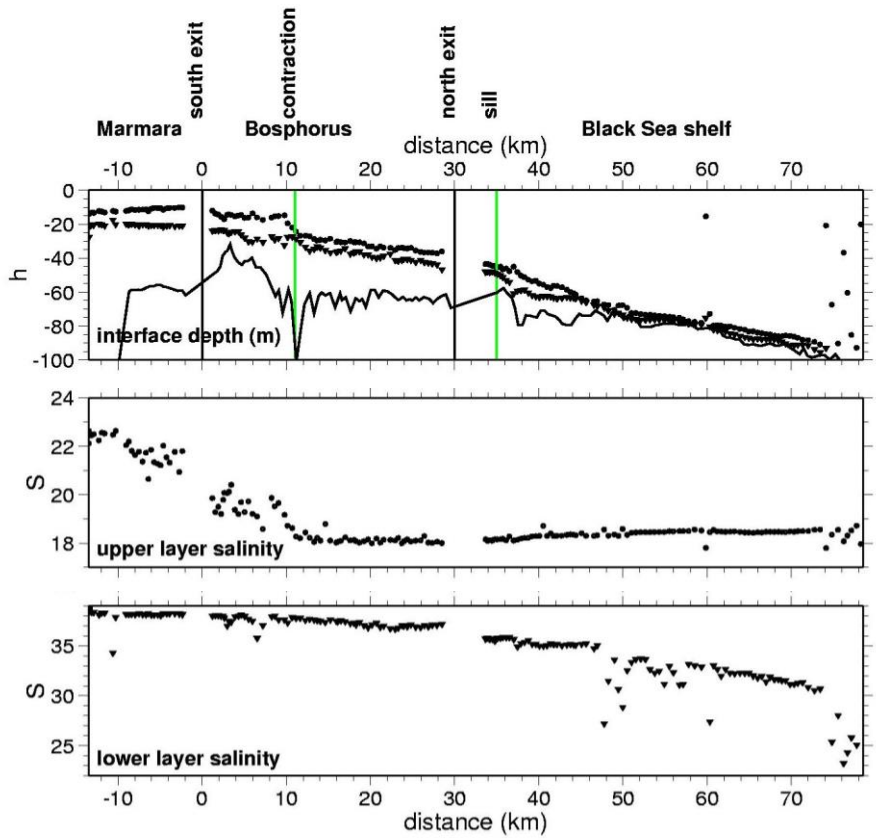

Fig. (5.12): Variation of the interface depth with the upper and lower layer salinity.

The results of the hydrodynamic simulation of the Bosphorus explains successfully the basic features of the quasi-steady flow structure and associated mixing and stratification characteristics in terms of internal hydraulics of the exchange flow. The flows in the layers are very compatible as compared to the field measurements.

However, the two-layer idealization of the flow structure has a deficiency that the control over the northern sill cannot be resolved properly by the simulation. Near the southern end of the strait, due to the intense vertical mixing, the surface and bottom layers are separated by a relatively broad interfacial layer. A three-layer extension of this present model, which incorporates the transitional layer separately and therefore leads to a better approximation of the bottom layer, is necessary to simulate the possible control at the southern sill. For this purpose, the scale of the computational domain has to be more detailed as compared to the whole area covering the strait in this study.

REFERENCES

Akyarlı, A. and Arısoy, Y., 1995. Oceanographic measurements for the tube-tunnel crossing of the Bosphorus, *International Journal of Offshore and Polar Engineering,* **5-2**, 98-104.

Farmer, D. M. and L. Armi., 1986. Maximal Two-Layer Exchange over a Sill and Through the Combination of a Sill and Contraction with Barotropic Flow, *J. Fluid Mech.*, **164**, 53-76.

Oğuz, T., Özsoy, E., Latif, M.A., Ünluata, U., 1990. Modeling of hydraulically controlled exchange flow in the Bosphorus Strait, *J. Phys. Oceanogr.*, **20**, 945–965.

Özsoy, E., Oğuz, T., Latif, M. A., Ünlüata Ü., Sur, H. İ. and Ş. Beşiktepe., 1988. Oceanography of the Turkish Straits - Second Annual Report, Volume I: *Physical Oceanography of the Turkish Straits*, Institute of Marine Sciences, METU, Erdemli, İçel.

Özsoy, E., Latif, M. A., Beşiktepe, Ş., Çetin, N., Gregg, M., Belokopytov, V., Goryachkin, Y. and D, Vassile., 1998. The Bosphorus Strait: Exchange Fluxes, Currents and Sea-Level Changes, in *Ecosystem Modeling as a Management Tool for the Black Sea*, *NATO Science Series 2: Environmental Security,* **1**, pp. 367, **2**, pp.385, Ed. L. I. Ivanov and T. Oğuz , Kluwer Academic Publishers, Dordrecht.

Özsoy, E., Beşiktepe, Ş., Latif, M. A., 2000a. Türk Boğazlar Sistemi'nin oşinografisi, *Marmara Denizi 2000 sempozyumu,* İstanbul, 11-12 November. (in Turkish).

Özsoy, E., Gregg, M., Fohrmann, H., Backhaus, J.O., 2000b. The Bosphorus Strait and its shelf outflow into the Black Sea: experiments and modeling. Oceanic Fronts and Related Phenomena, Proceedings of the Konstantin Fedorov International Memorial Symposium, St. Petersburg, International Oceanographic Commission Workshop Report No. 159, pp. 386–391.

Özsoy E., Di Iorio D., Gregg M. and Backhaus, J., 2001. Mixing in the Bosphorus Strait and the Black Sea Continental Shelf: Observations and a model of the dense water outflow, *J. Mar .Sys.*, **31**, 99-135.

Özsoy, E., Latif, M. A., Beşiktepe, Ş., 2002. The current system of the Bosphorus Strait based on recent measurements, *The 2nd Meeting on the Physical Oceanography of Sea Straits*, Villef ranche, 15-19 April, pp. 177-180.

Ünlüata, Ü., Oğuz, T., Latif, M. A., and Özsoy, E., 1990. On the physical oceanography of the Turkish Straits, *The Physical Oceanography of Sea Straits*, pp. 25-60, Ed. Pratt, L. J., NATO/ASI Series, Kluwer, Dordrecht.

Yüce, H., 1996. On the variability of Mediterranean water flow into the Black Sea, *Cont. Shlf. Res.*, **16-11**, 1399-1413.

APPENDIX 1: The Steering File

```
/-------------------------------------
/ Telemac3D v5p0 cas-file
/ all steering variables in english
/-------------------------------------
/
/
/
TELEMAC-3D RELEASE = V5P0
TELEMAC-2D RELEASE = V5P0
FORTRAN FILE = princi.f
GEOMETRY FILE = geofile
BOUNDARY CONDITIONS FILE = cnlmfile
3D RESULT FILE = sonuc3d
2D RESULT FILE = sonuc2d
STEERING FILE = cas
/
TITLE = 'Calculus 1 TELEMAC-3D/Hydrodynamic Simulation of the
Bosphorus'
COMPUTATION CONTINUED = NO
VARIABLES FOR 3D GRAPHIC PRINTOUTS = U,V,W
VARIABLES FOR 2D GRAPHIC PRINTOUTS = U,V,H,S,B
TIME STEP = 20
NUMBER OF TIME STEPS =1260
NUMBER OF FIRST TIME STEP FOR GRAPHIC PRINTOUTS = 1
GRAPHIC PRINTOUT PERIOD = 63
LISTING PRINTOUT PERIOD = 63
NUMBER OF HORIZONTAL LEVELS = 10
/
/---------------------------------------------------------------------
/         NUMERICAL OPTIONS
/---------------------------------------------------------------------
/
NUMBER OF SUB ITERATIONS FOR NON LINEARITIES = 1
/
SCHEME FOR ADVECTION OF VELOCITIES = 1
SCHEME FOR ADVECTION OF DEPTH= 5
SCHEME FOR DIFFUSION OF VELOCITIES = 1
/
INITIAL GUESS FOR DEPTH = 1
SOLVER FOR DIFFUSION OF VELOCITIES = 3
SOLVER FOR PROPAGATION = 3
SOLVER FOR VERTICAL VELOCITY = 3
/
PRECONDITIONING FOR PROPAGATION = 2
PRECONDITIONING FOR DIFFUSION OF VELOCITIES = 2
PRECONDITIONING FOR VERTICAL VELOCITY = 2
/
ACCURACY FOR DIFFUSION OF VELOCITIES = 1E-10
ACCURACY FOR PROPAGATION = 1E-10
ACCURACY FOR VERTICAL VELOCITY = 1E-10
/
```

APPENDIX 2: The Boundary Conditions File

Color code H U V	no use in TELEMAC-3D	Color code T	no use in TELEMAC-3D	mesh node number	global number
2 2 2	0.0 0.0 0.0 0.0	2	0.0 0.0 0.0	40	1
2 2 2	0.0 0.0 0.0 0.0	2	0.0 0.0 0.0	385	2
2 2 2	0.0 0.0 0.0 0.0	2	0.0 0.0 0.0	552	3
2 2 2	0.0 0.0 0.0 0.0	2	0.0 0.0 0.0	10947	4
2 2 2	0.0 0.0 0.0 0.0	2	0.0 0.0 0.0	145	5
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2378	6
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1534	7
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1688	8
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2471	9
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1977	10
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	519	11
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1670	12
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1423	13
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	73	14
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2324	15
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	352	16
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1072	17
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2445	18
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1466	19
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	543	20
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1244	21
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1220	22
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2410	23
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1396	24
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	516	25
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1375	26
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	262	27
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	980	28
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	556	29
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	165	30
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	246	31
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	946	32
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	2013	33
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1793	34
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1863	35
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	903	36
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1445	37
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1436	38
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1544	39
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	996	40
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	239	41
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1317	42
4 6 6	0.0 0.0 0.0 0.0	5	0.0 0.0 0.0	1073	43
-------	----------------------	--	-----------------	-------	---

APPENDIX 3: Subroutines from the TELEMAC-3D library

Subroutine BORD	Prescription of boundary conditions.
Subroutine CONDIM	Prescription of initial conditions.
Subroutine CORFON	Modification of bottom topography.
Subroutine DRIUTI	Damping function for viscosity.
Subroutine DRSURR	Computation of buoyancy term.
Subroutine FLOT3D	Initial positions of drogues.
Subroutine INBETA	Prescription of volumetric expansion coefficient.
Subroutine LIMTYP	Prescription of type of boundary conditions.
Program PRINCI	Sizing of memory space.
Subroutine SCOPE	Creation of 1D cross-sections.
Subroutine SOURCE	Prescription of tracer flow rates and source values.
Subroutine UTIMP	Printing of additional data.
Subroutine VISCO	Modification of viscosity.

APPENDIX 4: The Fortran File of the Bosphorus Simulation

```
                           PROGRAM PRINCI
C                          **************
C
C-------------------------------------------------------------------
----
C
C                       PROGRAMME PRINCIPAL DE
C
C    TTTTT  EEEEE  L      EEEEE  M   M  AAAAA   CCCC     33333  DDDD
C      T    E      L      E      MM MM  A   A  C            3  D
D
C      T    EEE    L      EEE    M M M  AAAAA  C     ---   333  D
D
C      T    E      L      E      M   M  A   A  C            3  D
D
C      T    EEEEE  LLLLL  EEEEE  M   M  A   A   CCCC     33333  DDDD
C
C                           RESOLUTION DES
C      EQUATIONS DE NAVIER-STOKES TRIDIMENSIONNELLES A SURFACE LIBRE
C
C-------------------------------------------------------------------
----
C
C     NOTE:
C
C     PRINCI NE SERT QU' A DIMENSIONNER LES TABLEAUX A ET I DANS
C     LESQUELS SERONT STOCKES TOUS LES TABLEAUX DE REELS ET
D'ENTIERS
C     DU PROGRAMME TELEMAC-3D EN FONCTION DU NOMBRE DE POINTS DANS
LE
C     MAILLAGE ET DES DIFFERENTES OPTIONS DE CALCUL.
C
      IMPLICIT NONE
      INTEGER LNG,LU
      COMMON/INFO/LNG,LU
C
      INTEGER IDIMA,IDIMI,NPRIV
      PARAMETER ( IDIMA=4400000  , IDIMI=530000)
      PARAMETER ( NPRIV= 0 )
      DOUBLE PRECISION A(IDIMA)
      INTEGER I(IDIMI)
      SAVE A,I
C
C     APRES UNE EXECUTION LA DIMENSION EXACTE DE A ET I EST
C     DONNEE DANS LE DEBUT DU LISTING.
C
C-------------------------------------------------------------------
----
C     CANAL DE SORTIE LISTING ET LANGUE
C
      LU = 6
      LNG = 2
C
C-------------------------------------------------------------------
----
C
```

```
      CALL PREMIT(A,IDIMA,I,IDIMI,NPRIV)
C
      IF (LNG.EQ.1) WRITE(LU,11)
      IF (LNG.EQ.2) WRITE(LU,12)
C
11    FORMAT(////,' FIN NORMALE DU PROGRAMME',/////)
12    FORMAT(////,' CORRECT END OF RUN',/////)
C
C-----------------------------------------------------------------------
----
C
      STOP
      END
```

```
!             *****************
              SUBROUTINE CONDIM
!             *****************
  & ( AT )
!
!***********************************************************************
! TELEMAC-3D   V2P2        25/11/97      J-M HERVOUET(LNH) 30 87 80 18
!                               F LEPEINTRE (LNH) 30 87 78 54
!                               J-M JANIN   (LNH) 30 87 72 84
! FORTRAN95 VERSION        MARCH 1999       JACEK A. JANKOWSKI PINXIT
!***********************************************************************
!
!    FONCTION:
!    =========
!
!   INITIALISATION DES TABLEAUX DES GRANDEURS PHYSIQUES
!
!-----------------------------------------------------------------------
!
! SOUS-PROGRAMME APPELE PAR : MITRID
! SOUS-PROGRAMMES APPELES : OV , (CALCOT)
!
!***********************************************************************
!
    USE BIEF
    USE DECLARATIONS_TELEMAC
    USE DECLARATIONS_TELEMAC3D
!
    IMPLICIT NONE
    INTEGER LNG,LU
    COMMON/INFO/LNG,LU
!
!-----------------------------------------------------------------------
!
    DOUBLE PRECISION, INTENT(OUT) :: AT
!
!-----------------------------------------------------------------------
!
    INTEGER IPLAN, I
!
!***********************************************************************
! TIME ORIGIN
!
    AT  = 0.D0
!
! INITIALISATION DE H , LA HAUTEUR D'EAU.
```

```
!
      CALL OS( 'X=C     ' , H   , H , H , 0.D0)
      CALL OV( 'X=X-Y   ' , H%R(1) , Z , Z , 0.D0 , NPOIN2 )
!
      DO I=1,NPOIN2
       H%R(I)=MAX(H%R(I),HMIN)
      ENDDO
!
! INITIALISATION OF THE FREE SURFACE
!
      IF (NONHYD) CALL OV( 'X=Y+Z   ', S%R(1), H%R(1), Z , 0.D0, NPOIN2)
!$DC$
! DELTACAD - INTRODUCTION MODIF HANOVRE :
!
      CALL OS ('X=Y     ', HN, H, H, 0.D0)

!-----------------------------------------------------------------------
!
!     INITIALISATION DE LA COTE DU PLAN INTERMEDIAIRE DE REFERENCE.
!     PAR DEFAUT, CE PLAN EST PLACE ENTRE FOND ET SURFACE AU PRORATA
!     DU PARAMETRE NPLINT.
!
! DOUBLED; Z => Z3%R(1) WHICH IS MESH3D%Z
!
!
!  NOTE JMH : POURQUOI FAIT-ON DEUX FOIS LA MEME CHOSE ?
!
      IF (NPLINT.GE.2) THEN
        Z( (NPLINT-1)*NPOIN2+1 : NPLINT*NPOIN2 ) = COTINT
        CALL OV( 'X=C     ' , Z((NPLINT-1)*NPOIN2+1 : NPLINT*NPOIN2),
     *               Z, Z, COTINT , NPOIN2)
!$DC$
!
!       NOTE JMH : QU'EST-CE QUE C'EST QUE CE TRUC ?
!       REPONSE TD : JUSQU'A NOUVEL ORDRE C'EST N'IMPORTE QUOI
!        CALL OS( 'X=C     ' , H , H , H , 0.D0)
      ENDIF
!
! ORIG. CODE
!
!      IF (NPLINT.GE.2) THEN
!        DO I=1,NPOIN2
!          Z(I,NPLINT)=COTINT
!        END DO
!      ENDIF
!
!-----------------------------------------------------------------------
!
!     INITIALISATION DE ZSTAR, LE RAPPORT ENTRE LA HAUTEUR D'EAU SOUS
!     UN PLAN QUASI HORIZONTAL ET LA HAUTEUR D'EAU TOTALE
!
! CAS SANS PLAN INTERMEDIAIRE DE REFERENCE
! ---------------------------------------
!
!         ON DOIT AVOIR :
!            * ZSTAR%R(1)     = 0.D0 ( PLAN DU FOND )
!            * ZSTAR%R(NPLAN) = 1.D0 ( PLAN DE LA SURFACE LIBRE )
!         ET POUR TOUT I COMPRIS ENTRE 1 ET NPLAN-1
!            * ZSTAR%R(I) < ZSTAR%R(I+1)
!
```

```
! CAS AVEC PLAN INTERMEDIAIRE DE REFERENCE
! ---------------------------------------
!
!       ON DOIT AVOIR :
!         * ZSTAR%R(1)      = -1.D0 ( PLAN DU FOND )
!         * ZSTAR%R(NPLINT) =  0.D0 ( PLAN INTERMEDIAIRE DE REFERENCE
!         * ZSTAR%R(NPLAN)  =  1.D0 ( PLAN DE LA SURFACE LIBRE )
!       ET POUR TOUT I COMPRIS ENTRE 1 ET NPLAN-1
!         * ZSTAR%R(I) < ZSTAR%R(I+1)
!
!    PAR DEFAUT, LES PLANS QUASI HORIZONTAUX SONT REGULIEREMENT ESPACES
!
!***********************************************************************
!    POUR DONNER VOTRE PROPRE REPARTITION DES PLANS, MODIFIEZ LES
!    BOUCLES 5 ET 10
!    REMARQUE : NPLINT=1 QUAND IL N'Y A PAS DE PLAN INTERMEDIAIRE
!    ATTENTION : EN CAS DE TRANSFORMATION SIGMA GENERALISEE,
!    ---------   ZSTAR(2) A ZSTAR(NPLAN-1) DOIVENT ETRE MODIFIEES
!             ET CONTENIR LA COTE DE POSITIONNEMENT DES DIFFERENTS
!             PLANS DU MAILLAGE (IL VA DE SOIT QUE CELLES-CI DOIVENT
!             ETRE DONNEES DANS UN ORDRE STRICTEMENT CROISSANT).
!***********************************************************************
!
      IF (NPLINT.GE.2) THEN
        DO IPLAN = 1,NPLINT-1
          ZSTAR%R(IPLAN) = DBLE(IPLAN-NPLINT)/DBLE(NPLINT-1)
        END DO
      ENDIF
!
      DO IPLAN = NPLINT,NPLAN
        ZSTAR%R(IPLAN) = DBLE(IPLAN-NPLINT)/DBLE(NPLAN-NPLINT)
      END DO
!
!***********************************************************************
!
! ON NE DISPOSE PAS AU DEBUT DE CE SOUS-PROG. DE Z EN TOUS LES POINTS.
! (CAR POUR CONNAITRE Z, IL FAUT CONNAITRE ZSTAR ET H).
! NEANMOINS, ON PEUT, A CETTE ETAPE DE LA ROUTINE, CALCULER Z.
! CELA PEUT SERVIR PAR EXEMPLE POUR INITIALISER VITESSES ET TRACEURS.
!
      CALL CALCOT
     & (Z, ZSTAR%R(1), H%R(1), NPOIN2, NPLAN, NPLINT, SIGMAG, HMIN, COTINT)
!
!***********************************************************************
!
!    INITIALISATION DES VITESSES
!
      CALL OS( 'X=C     ' , U , U , U , 0.0D0 )
      CALL OS( 'X=C     ' , V , V , V , 0.0D0 )
      CALL OS( 'X=C     ' , W , W , W , 0.0D0 )
!
!-----------------------------------------------------------------------
!
!    INITIALISATION DES TRACEURS ACTIFS
!
      IF (NTRAC.NE.0) THEN
        CALL OS( 'X=C     ', TA, TA, TA, 0.D0)
      ENDIF
!
!-----------------------------------------------------------------------
```

```
!
!    INITIALISATION DES TRACEURS PASSIFS
!
     IF (NTRPA.NE.0) THEN
       CALL OS( 'X=C     ', TP, TP, TP, 0.D0)
     ENDIF
!
!-----------------------------------------------------------------------
!   INITIALISATION DU MODELE K-EPSILON (FACULTATIF)
!   SI VOUS LE FAITES, INDIQUEZ AKEP = .FALSE.
!
!    IF(ITURB.EQ.3) THEN
!      AKEP = .FALSE.
!    ENDIF
!
!-----------------------------------------------------------------------
! INITIALIZE THE HYDRODYNAMIC PRESSURE FIELD TO 0.0
! (PROJECTION2: IT MAY BE APPROPRIATE TO SOLVE A POISSON EQUATION FOR DP
!
     IF(NONHYD) THEN
       CALL OS('X=C     ', DP, DP, DP, 0.0D0)
         WRITE (LU,*) 'CONDIM: DYNAMIC PRESSURE INITIALISED TO ZERO'
       CALL PHSTAT
    *      (PH%R(1),DELTAR%R(1),Z, T3_01%R(1), T3_02%R(1), RHO0, GRAV,
    *                    NPOIN3, NPOIN2, NPLAN, PRIVE )
!!!       WRITE (LU,*) 'CONDIM: HYDROSTATIC PRESSURE INITIALISED.'
     ENDIF
!
!-----------------------------------------------------------------------
!
     RETURN
     END

!                   *****************
                    SUBROUTINE BORD3D
!                   *****************
!
!$DC$
!   & (AT, LT, INFOGR)
    & (AT, LT, INFOGR, NPTFR2_DIM)
!
!***********************************************************************
! TELEMAC-3D   V2P3        29/10/98      T. DENOT (LNH) 01 30 87 74 89
! FORTRAN95 VERSION        MARCH 1999       JACEK A. JANKOWSKI PINXIT
!***********************************************************************
!
!     FONCTION:
!     =========
!
!   ACTUALISE LES CONDITIONS LIMITES 3D
!
!-----------------------------------------------------------------------
!                        ARGUMENTS
! .________________.____.______________________________________________.
! !  NOM          !MODE!               ROLE                     !
! !________________!____!______________________________________________!
! !  UBORF,L,S     !<-- ! VITESSE U AU BORD : FOND, COTES ET SURFACE   !
! !  VBORF,L,S     !<-- ! VITESSE V AU BORD : FOND, COTES ET SURFACE   !
! !  WBORF,L,S     !<-- ! VITESSE W AU BORD : FOND, COTES ET SURFACE   !
! !  TABORF,L,S    !<-- ! TRACEUR ACTIF AU BORD :FOND, COTES ET SURFACE!
```

```
! !  TPBORF,L,S    !<-- ! TRACEUR PASSIF AU BORD:FOND, COTES ET SURFACE!
! !               !    !                                      !
! !               !    !ATTENTION : ON SE DONNE LA CONTRAINTE NU*DU/DN!
! !               !    !*********                             !
! ! AUBOR,BUBOR    !<-- ! LOI LOG SUR LA VITESSE U : AUBOR*U + BUBOR   !
! ! AUBOR,BVBOR    !<-- ! LOI LOG SUR LA VITESSE V : AUBOR*V + BVBOR   !
! ! ATABO,BTABO    !<-- ! LOI LOG SUR TRACEURS ACTIFS: ATABO*TA + BTABO!
! ! ATPBO,BTPBO    !<-- ! LOI LOG SUR TRACEURS PASSIFS:ATPBO*TP + BTPBO!
! !  F, L, S       !    ! F : FOND   L : COTES LATERAUX  S : SURFACE   !
! !  LIU,V,WBOF    !<-->! TYPE COND. LIMITES SUR U,V,W      : FOND     !
! !  LIU,V,WBOL    !<-->! TYPE COND. LIMITES SUR U,V,W      : COTES    !
! !  LIU,V,WBOS    !<-->! TYPE COND. LIMITES SUR U,V,W      : SURFACE  !
! !  LITA,TP,BF    !<-->! TYPE COND. LIMITES SUR TA,TP      : FOND     !
! !  LITA,TP,BL    !<-->! TYPE COND. LIMITES SUR TA,TP      : COTES    !
! !  LITA,TP,BS    !<-->! TYPE COND. LIMITES SUR TA,TP      : SURFACE  !
! !  U,V,W         ! -->! VITESSE 3D                            !
! !  UMOY,VMOY     ! -->! VITESSE 2D (U , V MOYENNEES SUR LA VERTICALE)!
! !  TA            ! -->! CONCENTRATIONS DES TRACEURS ACTIFS          !
! !  ITURB         ! -->! MODELE DE TURBULENCE (1:LAMINAIRE 2: LG MEL) !
! !  RUGO          !<-->! COEFFICIENTS DE RUGOSITE PAR POINT FRONTIERE !
! !  RUGOF0        ! -->! COEFFICIENT DE RUGOSITE CONSTANT AU FOND     !
! !  RUGOL0        ! -->! COEFFICIENT DE RUGOSITE CONSTANT SUR PAROIS  !
! !  WC            ! -->! VITESSE DE CHUTE DU SEDIMENT                 !
! !                !    ! SI IL Y A UN SEDIMENT, SA CONCENTRATION EST  !
! !                !    ! DANS TA(1,NTRAC)                      !
! !  VENT          ! -->! AVEC(.TRUE.) OU SANS(.FALSE.) VENT           !
! !  FAIR          ! -->! COEFFICIENT D'INFLUENCE DU VENT              !
! !  VENTX         ! -->! VITESSE DU VENT SUIVANT X                    !
! !  VENTY         ! -->! VITESSE DU VENT SUIVANT Y                    !
! !  AT            ! -->! TEMPS DU PAS DE TEMPS                        !
! !  LT            ! -->! NUMERO DU PAS DE TEMPS                       !
! !  DT            ! -->! PAS DE TEMPS                          !
! !  LIHBOR        ! -->! TYPE COND. LIMITES SUR H                     !
! !  HBOR          ! -->! HAUTEUR AU BORD                              !
! !  HN            ! -->! HAUTEUR A L'INSTANT N                        !
! !  X,Y,Z         ! -->! COORDONNEES DU MAILLAGE                      !
! !  ZF            ! -->! COTES DU FOND                         !
! !  TRA01,2       ! -->! TABLEAUX DE TRAVAIL                          !
! !  NBOR          ! -->! NUMERO GLOBAL DES POINTS FRONTIERE 2D        !
! !  NELEM3        ! -->! NOMBRE D'ELEMENTS 3D                         !
! !  IKLE3         ! -->! TABLE DE CONNECTIVITE 3D                     !
! !  KP1BOR        ! -->! PT FRONT. SUIVANT LE PT FRONT. CONSIDERE     !
! ! XSGBOR,YSGBOR  ! -->! COORDONNEES VECTEUR NORMAL SEG. BORD 2D      !
! !  NPOIN3        ! -->! NOMBRE DE POINTS 3D                          !
! !  NPOIN2        ! -->! NOMBRE DE POINTS 2D                          !
! !  NETAGE        ! -->! NOMBRE D'ETAGES                              !
! !  NPTFR         ! -->! NOMBRE DE POINTS FRONTIERE 2D                !
! !  NPTFR3        ! -->! NOMBRE DE POINTS FRONTIERE 3D COTES LATERAUX !
! !  NPLAN         ! -->! NOMBRE DE PLANS SUR LA VERTICALE             !
! !  NELEM2        ! -->! NOMBRE D'ELEMENTS 2D                         !
! !  KENT          ! -->! INDICATEUR DE POINT D'ENTREE FLUIDE (IMPOSE) !
! !  KENTU         ! -->! INDICATEUR DE POINT D'ENTREE FLUIDE
! !                !    ! (DEBIT IMPOSE)                        !
! !  KSORT         ! -->! INDICATEUR DE POINT DE SORTIE FLUIDE (LIBRE) !
! !  KADH          ! -->! INDICATEUR DE POINT D'ADHERENCE              !
! !  KLOG          ! -->! INDICATEUR DE PAROI SOLIDE                   !
! !  NTRAC         ! -->! NOMBRE DE TRACEURS ACTIFS                    !
! !  NTRPA         ! -->! NOMBRE DE TRACEURS PASSIFS                   !
! !  SEDI          ! -->! LOGIQUE INDIQUANT SI IL Y A UN SEDIMENT      !
! !  PRIVE         ! -->! TABLEAUX RESERVES A L'UTILISATEUR            !
```

```
! !  NPRIV        ! -->! NOMBRE DE TABLEAUX DE DIMENSION NPOIN3      !
! !              !    ! RESERVES A L'UTILISATEUR                   !
! !  NDEBIT       ! -->! NBRE DE FRONTIERES LIQUIDES A DEBIT IMPOSE   !
! !  NVIT         ! -->! NBRE DE FRONTIERES LIQUIDES A VITESSE IMPOSEE!
! !  NCOTE        ! -->! NBRE DE FRONTIERES LIQUIDES A COTE IMPOSEE   !
! !  DEBIMP       ! -->! TABLEAU CONTENANT LES DEBITS DES FRONTIERES  !
! !              !    ! LIQUIDES A DEBIT IMPOSE                    !
! !  COTIMP       ! -->! TABLEAU CONTENANT LES COTES DES FRONTIERES   !
! !              !    ! LIQUIDES A COTE IMPOSEE                    !
! !  VITIMP       ! -->! TABLEAU CONTENANT LES VITESSES DES FRONTIERES!
! !              !    ! LIQUIDES A VITESSE IMPOSEE                 !
! !________________!____!______________________________________________!
! MODE : -->(DONNEE NON MODIFIEE), <--(RESULTAT), <-->(DONNEE MODIFIEE)
!
!-----------------------------------------------------------------------
!
! SOUS-PROGRAMME APPELE PAR : MITRID
! SOUS-PROGRAMMES APPELES : OV
!
!***********************************************************************
!                                                                      *
! ATTENTION: LES CONDITIONS AUX LIMITES SUR LES POINTS APPARTENANT     *
!            ------                                                    *
!            A LA FOIS AUX COTES LATERAUX ET A LA SURFACE OU AU FOND   *
!            SONT A IMPOSER PAR LES TABLEAUX CORRESPONDANT AUX COTES   *
!            LATERAUX (LETTRE L A LA FIN DU NOM DU TABLEAU)            *
!            UNE CONDITION IMPOSEE AUTREMENT N'EST PAS PRISE EN COMPTE *
!                                                                      *
!      CE SOUS-PROGRAMME EST A COMPLETER PAR L'UTILISATEUR             *
!      (VOIR AUSSI LIMTYP)                                             *
!                                                                      *
!      ICI, ON FIXE LA VALEUR DES CONDITIONS AUX LIMITES (UBORF...)   *
!      LA NATURE DES CONDITIONS AUX LIMITES EST DONNEE DANS LIMTYP    *
!      (LIUBOF...)                                                     *
!                                                                      *
!      SI IL Y A UN SEDIMENT, SA CONCENTRATION EST DANS TA(1,NTRAC)   *
!                                                                      *
!***********************************************************************
!
      USE BIEF
      USE DECLARATIONS_TELEMAC
      USE DECLARATIONS_TELEMAC3D
!
      IMPLICIT NONE
      INTEGER LNG,LU
      COMMON/INFO/LNG,LU

      DOUBLE PRECISION, INTENT(IN) :: AT
      INTEGER, INTENT(IN) :: LT
      LOGICAL, INTENT(IN) :: INFOGR
!$DC$
      INTEGER, INTENT(IN) :: NPTFR2_DIM
!
!-----------------------------------------------------------------------
!
      INTEGER I, IPOIN2, NP, K1, IBORD, IVIT, ICOT, IDEB
      DOUBLE PRECISION ROEAU, ROAIR, VITV
      INTEGER IPTFR, ITRPA, ITRAC

C     PARAMETRES POUR LA DETERMINATION DES FRONTIERES LIQUIDES
```

```
C       *****************************************************
C
      INTEGER NFRLIQ,NFRSOL
      INTEGER K
      INTEGER DEBLIQ(10),FINLIQ(10)
      INTEGER DEBSOL(10),FINSOL(10)
      INTEGER DEJAVU(NPTFR2_DIM),N
!
      INTEGER  P_IMAX
      EXTERNAL P_IMAX
!
!------------------------------------------------------------
!     Additions by user

      DOUBLE PRECISION QREF,SREF,Q
      DATA QREF,SREF /5500.,0./

      IF (AT.LT.3600.) THEN
        Q = QREF * (AT/3600.)
       ELSE
        Q = QREF
      ENDIF
      PRINT * ,'FRONTIERE A DEBIT IMPOSE: ',Q
!
! *******************************************************************
!
! -------------------------------
! CHANGEMENTS POUR LA VERSION 2.3
! -------------------------------
!
! BORD3D GERE MAINTENANT AUTOMATIQUEMENT LES FRONTIERES LATERALES
! POUR DES CAS SIMPLES
!
! 3 TYPES DE FRONTIERES :
!     -HAUTEUR IMPOSEE (5 4 4)
!     -VITESSE IMPOSEE (4 5 5)
!     -DEBIT IMPOSE    (4 6 6)
!
! LES MOTS CLES ASSOCIES SONT RESPECTIVEMENT
!     'COTES IMPOSEES'
!     'VITESSES IMPOSEES'
!     'DEBITS IMPOSES'
!
! ATTENTION : LA CONDITION 4 5 5 CORRESPOND A UNE CONDITION
! DE VITESSE IMPOSEE , CE QUI EST INCOHERENT AVEC TELEMAC-2D
! MAIS NE CHANGE RIEN POUR LES HABITUES DE TELEMAC-3D
!
! POUR DEBITS IMPOSEES, UTILISER 4 6 6
!
! POUR LES NOSTALGIQUES OU POUR DES CONDITIONS PLUS COMPLIQUEES
! PROGRAMMER LA ROUTINE COMME AVANT : IL EST ALORS CONSEILLE D'EFFACER
! TOUTES LES LIGNES CONCERNANT LA GESTION AUTOMATIQUE DES FRONTIERES
! (INDIQUEES DANS LE PROGRAMME)
! ON RETROUVE ALORS L' "ANCIEN" BORD3D
!
! REMARQUE : LA ROUTINE Q3D EST UTILISABLE POUR IMPOSER DES DEBITS
! (TELLE QUELLE OU A MODIFIER POUR DES BESOINS PARTICULIERS)
!
! *******************************************************************
!
```

```
!
! +++++++++++++++++++++++++++++++++++++++++++++++
! DEBUT DE LA GESTION AUTOMATIQUE DES FRONTIERES
! +++++++++++++++++++++++++++++++++++++++++++++++
!
! DEFINITION DES FRONTIERES LIQUIDES
!
! ON UTILISE LA ROUTINE FRONT2 DE TELEMAC-2D
! AUCUNE MODIF NECESSAIRE
! ON RECUPERE LE NOMBRE DE FRONTIERES LIQUIDES
! ET TOUS LES PARAMETRES ASSOCIES
!
!JMH
      IF(NCSIZE.GT.1) THEN
       NFRLIQ=0
       DO I=1,NPTFR2
         NFRLIQ=MAX(NFRLIQ,NUMLIQ%I(I))
       END DO
       NFRLIQ=P_IMAX(NFRLIQ)
       IF (INFOGR) THEN
         WRITE(LU,*) ' '
         IF(LNG.EQ.1)
     &     WRITE(LU,*) 'NOMBRE DE FRONTIERES LIQUIDES :',NFRLIQ
         IF(LNG.EQ.2)
     &     WRITE(LU,*) 'NUMBER OF LIQUID BOUNDARIES:',NFRLIQ
       ENDIF
      ELSE
! NOTICE: CALL LIUBOL%I(1)
       CALL FRONT2(NFRLIQ, NFRSOL, DEBLIQ, FINLIQ,
     &             DEBSOL, FINSOL, LIHBOR%I(1), LIUBOL%I(1), X, Y,
     &             NBOR2%I(1), MESH2D%KP1BOR%I(1), DEJAVU,
     &             NPOIN2, NPTFR2, KLOG, INFOGR, NUMLIQ%I(1))
      ENDIF
! NOT CHANGED FROM FORTRAN77
!     CALL FRONTI
!    &(NFRLIQ,NFRSOL,DEBLIQ,FINLIQ,DEBSOL,FINSOL,LIHBOR,X,Y,
!    & NBOR,KP1BOR,DEJAVU,NPOIN2,NPTFR,KLOG,.FALSE.)
!JMH
      IDEB=0
      ICOT=0
      IVIT=0
!
! ****************************************
! RECHERCHE SEGMENT A DEBIT IMPOSE (4 6 6)
! ****************************************
!
      DO N=1,NFRLIQ
      K=DEBLIQ(N)
      IF (LIHBOR%I(K).EQ.KSORT.AND.
     &    LIUBOL%I(K).EQ.KENTU.AND.
     &    LIVBOL%I(K).EQ.KENTU) THEN
      IDEB=IDEB+1
!
        IF (IDEB.LE.NDEBIT) THEN
          CALL Q3D
     &      (HN%R(1), X3%R(1), Y3%R(1), UBORL%R(1), VBORL%R(1), WBORL%R(1),
     &       XSGBOR2, YSGBOR2, Q, NBOR2,
     &       NPOIN2, NPLAN, NPTFR2, DEBLIQ(N), FINLIQ(N),
     &       MESH2D%KP1BOR%i(1))
        ELSE
```

```
        IF(LNG.EQ.1 .AND. INFOGR) WRITE(LU,100) IDEB,NDEBIT
100     FORMAT(1X,'                                    ',/,
     &        1X,'BORD3D : PROBLEME SUR LES CONDITIONS AUX LIMITES',/,
     &        1X,'                                    ',/,
     &        1X,'VOUS AVEZ ',1I2,' FRONTIERES A DEBIT IMPOSE',/,
     &        1X,'MAIS VOUS FIXEZ SEULEMENT',1I2,' DEBITS',/,
     &        1X,'DANS VOTRE FICHIER DES PARAMETRES       ')
        IF(LNG.EQ.2 .AND. INFOGR) WRITE(LU,101) IDEB,NDEBIT
101     FORMAT(1X,'                                    ',/,
     &        1X,'BORD3D : PROBLEM ON BOUNDARY CONDITIONS        ',/,
     &        1X,'                                    ',/,
     &     1X,'YOU HAVE ',1I2,' BOUNDARIES WITH PRESCRIBED FLOWRATES',/,
     &        1X,'BUT YOU ONLY PRESCRIBE',1I2,' FLOWRATES',/,
     &        1X,'IN YOUR STEERING FILE      ')
        STOP
!
      ENDIF
     ENDIF
     END DO

!
! ****************************************************
! RECHERCHE SEGMENT A VITESSE IMPOSE (4 5 5)
! ****************************************************
!
     DO N=1,NFRLIQ
!
       K=DEBLIQ(N)
!       ----------------------------
       IF (LIHBOR%I(K).EQ.KSORT.AND.
     &   LIUBOL%I(K).EQ.KENT.AND.
     &   LIVBOL%I(K).EQ.KENT) THEN
!       ----------------------------
       IVIT=IVIT+1
!
         IF (IVIT.LE.NVIT) THEN
          K1=K
!
 31        IF (K.NE.FINLIQ(N)) THEN
!
          DO NP=1,NPLAN
           IBORD = (NP-1)*NPTFR2 + K
           UBORL%R(IBORD) = -MESH2D%XSGBOR%R(K)*VITIMP(IVIT)
           VBORL%R(IBORD) = -MESH2D%YSGBOR%R(K)*VITIMP(IVIT)
           WBORL%R(IBORD) = 0.D0
          END DO
!
          ELSE
!
          DO NP=1,NPLAN
           IBORD = (NP-1)*NPTFR2+K
           UBORL%R(IBORD) = -MESH2D%XSGBOR%R(K1)*VITIMP(IVIT)
           VBORL%R(IBORD) = -MESH2D%YSGBOR%R(K1)*VITIMP(IVIT)
           WBORL%R(IBORD) = 0.D0
           END DO
          GOTO 35
!
          ENDIF
!
       K1=K
```

```
        K=MESH2D%KP1BOR%I(K)
        GOTO 31
!
 35     CONTINUE
!
          ELSE
!
         IF(LNG.EQ.1) WRITE(LU,200) IVIT,NVIT
200     FORMAT(1X,'                                    ',/,
    &        1X,'BORD3D : PROBLEME SUR LES CONDITIONS AUX LIMITES',/,
    &        1X,'                                    ',/,
    &        1X,'VOUS AVEZ ',1I2,' FRONTIERES A VITESSE IMPOSEE',/,
    &        1X,'MAIS VOUS FIXEZ SEULEMENT',1I2,' VITESSES',/,
    &        1X,'DANS VOTRE FICHIER DES PARAMETRES      ')
         IF(LNG.EQ.2) WRITE(LU,201) IVIT,NVIT
201     FORMAT(1X,'                                    ',/,
    &        1X,'BORD3D : PROBLEM ON BOUNDARY CONDITIONS',/,
    &        1X,'                                    ',/,
    &    1X,'YOU HAVE ',1I2,' BOUNDARIES WITH PRESCRIBED VELOCITIES',/,
    &        1X,'BUT YOU ONLY PRESCRIBE',1I2,' VELOCITIES',/,
    &        1X,'IN YOUR STEERING FILE      ')
         STOP
!
          ENDIF
!       -----
        ENDIF
!       -----
!
      END DO
!
! *******************************************
! RECHERCHE SEGMENT A HAUTEUR IMPOSEE (5 4 4)
! *******************************************
!
      DO N=1,NFRLIQ
      K=DEBLIQ(N)
!
      IF (LIHBOR%I(K).EQ.KENT) THEN
      ICOT=ICOT+1
!
          IF (ICOT.LE.NCOTE) THEN
!
! 30          HBOR%R(K) = COTIMP(ICOT)-ZF%R(NBOR2%I(K))
 30         HBOR%R(K) = SREF-ZF%R(NBOR2%I(K))
           IF (K.EQ.FINLIQ(N)) GOTO 40
           K=MESH2D%KP1BOR%I(K)
           GOTO 30
 40   CONTINUE
!
          ELSE

         IF(LNG.EQ.1) WRITE(LU,300) ICOT,NCOTE
300     FORMAT(1X,'                                    ',/,
    &        1X,'BORD3D : PROBLEME SUR LES CONDITIONS AUX LIMITES',/,
    &        1X,'                                    ',/,
    &        1X,'VOUS AVEZ ',1I2,' FRONTIERES A COTE IMPOSEE',/,
    &        1X,'MAIS VOUS FIXEZ SEULEMENT',1I2,' COTES',/,
    &        1X,'DANS VOTRE FICHIER DES PARAMETRES      ')
         IF(LNG.EQ.2) WRITE(LU,301) ICOT,NCOTE
301     FORMAT(1X,'                                    ',/,
```

```
     &        1X,'BORD3D : PROBLEM ON BOUNDARY CONDITIONS',/,
     &        1X,'                                          ',/,
     &    1X,'YOU HAVE ',1I2,' BOUNDARIES WITH PRESCRIBED ELEVATIONS',/,
     &        1X,'BUT YOU ONLY PRESCRIBE',1I2,' ELEVATIONS',/,
     &        1X,'IN YOUR STEERING FILE      ')
          STOP
!
           ENDIF
!
!
      ENDIF
      END DO

!
! ++++++++++++++++++++++++++++++++++++++++++++++
! FIN DE LA GESTION AUTOMATIQUE DES FRONTIERES
! ++++++++++++++++++++++++++++++++++++++++++++++
!
      IF (VENT) THEN
        ROEAU = 1000.D0
        ROAIR = 1.3D0
        WINDDO: DO IPOIN2 = 1,NPOIN2
          VITV  = SQRT(WIND%ADR(1)%P%R(IPOIN2)**2
     &                + WIND%ADR(2)%P%R(IPOIN2)**2)
!
! CALCUL PLUS PRECIS DU COEFFICIENT D'INFLUENCE DU VENT
!
!CX        IF (VITV.LE.5.D0) THEN
!CX          FAIR = ROAIR/ROEAU*0.565D-3
!CX        ELSEIF (VITV.LE.19.22D0) THEN
!CX          FAIR = ROAIR/ROEAU*(-0.12D0+0.137D0*VITV)*1.D-3
!CX        ELSE
!CX          FAIR = ROAIR/ROEAU*2.513D-3
!CX        ENDIF
!
! ATTENTION : BUBORS CONTIENT VISCVI*DU/DN PAR DEFINITION DE LA
!           CONTRAINTE DUE AU VENT
!
          BUBORS%R(IPOIN2) = FAIR*VITV*WIND%ADR(1)%P%R(IPOIN2)
          BVBORS%R(IPOIN2) = FAIR*VITV*WIND%ADR(2)%P%R(IPOIN2)
        END DO WINDDO
      ENDIF
!
!    LES LIGNES QUI SUIVENT SONT A DECOMMENTARISER DANS LE CAS
!    D'ECHANGES THERMIQUES AVEC L'ATMOSPHERE
!
!    A REMPLIR :
!    ITEMP = NUMERO DU TRACEUR ACTIF REPRESENTANT LA TEMPERATURE DE
!          LA MER
!    TAIR  = TEMPERATURE DE L'AIR SUPPOSEE UNIFORME ET CONSTANTE
!    SAL   = SALINITE DE L'EAU SUPPOSEE UNIFORME ET CONSTANTE
!
!C    ITEMP=1
!C    CP=4.18D3
!C    RO0=999.972D0
!C    B=0.0025D0
!C    TAIR=15.D0
!C    SAL=35.D-3
!C    WW=0.D0
!C    IF (VENT) WW=VITV
```

```
!C    DO IPOIN2=1,NPOIN2
!C       TREEL=TA%ADR(ITEMP)%P%R(NPOIN3-NPOIN2+IPOIN2)
!C       RO=RO0*(1.D0-(7.D0*(TREEL-4.D0)*(TREEL-4.D0)-750.D0*SAL)*1D-6)
!C       LAMB=RO*CP
!C       A=(4.48D0+0.049D0*TREEL)+2021.5D0*B*(1.D0+WW)*
!C   &     (1.12D0+0.018D0*TREEL+0.00158D0*TREEL*TREEL)
!C       ATABOS%ADR(ITEMP)%P%R(IPOIN2)=-A/LAMB
!C       BTABOS%ADR(ITEMP)%P%R(IPOIN2)=-A/LAMB*(TMER-TAIR)
!C    END DO
!
!-----------------------------------------------------------------------
! JAJ TEST (AND AN EXAMPLE...)
!
!     DO IPTFR=1,NPTFR2
!       IF (LIHBOR%I(IPTFR) == KENT) HBOR%R(1) = 4.0D0
!     END DO
!
!     DO IBORD = 1, NPTFR3
!       IF (LIUBOL%I(IBORD) == KENT) UBORL%R(IBORD)  = 1.0D0
!       IF (LIVBOL%I(IBORD) == KENT) VBORL%R(IBORD)  = 0.0D0
!       IF (LIWBOL%I(IBORD) == KENT) WBORL%R(IBORD)  = 0.0D0
!       IF (LIUBOL%I(IBORD) == KLOG) AUBORL%R(IBORD) = 0.0D0
!       IF (LIUBOL%I(IBORD) == KLOG) BUBORL%R(IBORD) = 0.0D0
!       IF (LIVBOL%I(IBORD) == KLOG) BVBORL%R(IBORD) = 0.0D0
!     END DO
!
!     DO IPOIN2 = 1, NPOIN2
!       IF (LIUBOS%I(IPOIN2) == KENT) UBORS%R(IPOIN2)  = 1.0D0
!       IF (LIVBOS%I(IPOIN2) == KENT) VBORS%R(IPOIN2)  = 0.0D0
!       IF (LIWBOS%I(IPOIN2) == KENT) WBORS%R(IPOIN2)  = 0.0D0
!       IF (LIUBOS%I(IPOIN2) == KLOG) AUBORS%R(IPOIN2) = 0.0D0
!       IF (LIUBOS%I(IPOIN2) == KLOG) BUBORS%R(IPOIN2) = 0.0D0
!       IF (LIVBOS%I(IPOIN2) == KLOG) BVBORS%R(IPOIN2) = 0.0D0
!     END DO
!
!     DO IPOIN2 = 1, NPOIN2
!       IF (LIUBOF%I(IPOIN2) == KENT) UBORF%R(IPOIN2)  = 1.0D0
!       IF (LIVBOF%I(IPOIN2) == KENT) VBORF%R(IPOIN2)  = 0.0D0
!       IF (LIWBOF%I(IPOIN2) == KENT) WBORF%R(IPOIN2)  = 0.0D0
!       IF (LIUBOF%I(IPOIN2) == KLOG) AUBORF%R(IPOIN2) = 0.0D0
!       IF (LIUBOF%I(IPOIN2) == KLOG) BUBORF%R(IPOIN2) = 0.0D0
!       IF (LIVBOF%I(IPOIN2) == KLOG) BVBORF%R(IPOIN2) = 0.0D0
!     END DO
!
! WITHOUT CHECKING BC ATTRIBUTE (TYPE)
!
!     IF (NTRAC.GT.0) THEN
!       DO ITRAC =1,NTRAC
!         DO IPOIN2=1,NPOIN2
!           TABORF%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!           ATABOF%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!           BTABOF%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!           TABORS%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!           ATABOS%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!           BTABOS%ADR(ITRAC)%P%R(IPOIN2) = 0.D0
!         END DO
!         DO IBORD=1,NPTFR3
!           TABORL%ADR(ITRAC)%P%R(IBORD) = 0.D0
!           ATABOL%ADR(ITRAC)%P%R(IBORD) = 0.D0
!           BTABOL%ADR(ITRAC)%P%R(IBORD) = 0.D0
```

```
!        END DO
!      END DO
!    ENDIF
!
!    IF (NTRPA.GT.0) THEN
!      DO ITRPA =1,NTRPA
!        DO IPOIN2=1,NPOIN2
!          TPBORF%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!          ATPBOF%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!          BTPBOF%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!          TPBORS%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!          ATPBOS%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!          BTPBOS%ADR(ITRPA)%P%R(IPOIN2) = 0.D0
!        END DO
!        DO IBORD=1,NPTFR3
!          TPBORL%ADR(ITRPA)%P%R(IBORD) = 0.D0
!          ATPBOL%ADR(ITRPA)%P%R(IBORD) = 0.D0
!          BTPBOL%ADR(ITRPA)%P%R(IBORD) = 0.D0
!        END DO
!      END DO
!    ENDIF
!
!-----------------------------------------------------------------------
!
      RETURN
      END SUBROUTINE BORD3D

!                   **************
                    SUBROUTINE Q3D
!                   **************
!
     & (H, X, Y, UBOR, VBOR, WBOR, XSGBOR, YSGBOR, QREF, NBOR,
     &  NPOIN2, NPLAN, NPTFR, NDEB, NFIN, KP1BOR)
!
!***********************************************************************
! TELEMAC-3D   V2P3        29/10/98      T. DENOT (LNH) 01 30 87 74 89
! FORTRAN95 VERSION        MARCH 1999        JACEK A. JANKOWSKI PINXIT
!***********************************************************************
!
!    FONCTION:
!    =========
!
!   CE SOUS-PROGRAMME CALCULE LES VITESSES AUX POINTS FRONTIERES
!   DANS LE CAS D'UNE FRONTIERE LIQUIDE A DEBIT IMPOSE
!
!
!-----------------------------------------------------------------------
!                           ARGUMENTS
! .________________.____.______________________________________________.
! !  NOM           !MODE!                ROLE                          !
! !________________!____!______________________________________________!
! !  UBOR          !<-- ! VITESSE U AU BORD                            !
! !  VBOR          !<-- ! VITESSE V AU BORD                            !
! !  WBOR          !<-- ! VITESSE W AU BORD                            !
! !  H             ! -->! HAUTEUR D'EAU                                !
! !  X,Y           ! -->! COORDONNEES HORIZONTALES DU MAILLAGE         !
! ! XSGBOR,YSGBOR  ! -->! COORDONNEES VECTEUR NORMAL SEG. BORD 2D      !
! !  QREF          ! -->! DEBIT DE REFERENCE                           !
! !  NBOR          ! -->! NUMEROS GLOBAUX DES POINTS FRONTIERES 2D     !
! !  NPOIN2        ! -->! NOMBRE DE POINTS 2D                          !
```

```
! !  NPLAN        ! -->! NOMBRE DE PLANS SUR LA VERTICALE            !
! !  NPTFR        ! -->! NOMBRE DE POINTS FRONTIERE 2D               !
! !  NDEB         ! -->! INDICE DE DEBUT DE LA FONTIERE CONSIDEREE    !
! !  NFIN         ! -->! INDICE DE FIN DE LA FONTIERE CONSIDEREE      !
! !  KP1BOR       ! -->! PT FRONT. SUIVANT LE PT FRONT. CONSIDERE     !
! !________________!____!______________________________________________!
! MODE : -->(DONNEE NON MODIFIEE), <--(RESULTAT), <-->(DONNEE MODIFIEE)
!
      IMPLICIT NONE
!
      INTEGER, INTENT(IN) :: NPOIN2, NPLAN, NPTFR, NDEB, NFIN
      INTEGER, INTENT(IN) :: NBOR(NPTFR), KP1BOR(NPTFR)
!
      DOUBLE PRECISION, INTENT(IN)    :: H(NPOIN2)
      DOUBLE PRECISION, INTENT(IN)    :: X(NPOIN2), Y(NPOIN2)
      DOUBLE PRECISION, INTENT(INOUT) :: UBOR(NPTFR,NPLAN)
      DOUBLE PRECISION, INTENT(INOUT) :: VBOR(NPTFR,NPLAN)
      DOUBLE PRECISION, INTENT(INOUT) :: WBOR(NPTFR,NPLAN)
      DOUBLE PRECISION, INTENT(IN)    :: XSGBOR(NPTFR), YSGBOR(NPTFR)
!
      INTEGER N, N1, NP
      DOUBLE PRECISION S, D, UM, QREF
!
!-----------------------------------------------------------------------
! TOO MANY GOTO JUMPS
!
      S=0
!
! CALCUL DE LA SURFACE MOUILLEE S
!
      N=NDEB
 10   N1=KP1BOR(N)
!
      IF (N.EQ.NFIN) GOTO 20
      D=DSQRT( (X(NBOR(N1))-X(NBOR(N)))**2 +
     *         (Y(NBOR(N1))-Y(NBOR(N)))**2 )
      S=S+(H(NBOR(N))+H(NBOR(N1)))*0.5D0*D
      N=N1
      GOTO 10
!
! ON A S ET QREF, ON PEUT FIXER LES VITESSES AUX POINTS FRONTIERES
! ELLES SERONT ORTHOGONALES A LA FRONTIERE
!
 20   UM=QREF/S
      N=NDEB
      N1=N
!     ******************
 30   IF (N.NE.NFIN) THEN
!     ******************
!
      DO 40 NP=1,3
        UBOR(N,NP) = XSGBOR(N)*UM
        VBOR(N,NP) = YSGBOR(N)*UM
        WBOR(N,NP) = 0.D0
 40   CONTINUE
      DO 80 NP=4,NPLAN
        UBOR(N,NP) = -XSGBOR(N)*UM*2
        VBOR(N,NP) = -YSGBOR(N)*UM*2
        WBOR(N,NP) = 0.D0
 80   CONTINUE
```

```
!
!    ****
     ELSE
!    ****
!
     DO 50 NP=1,3
       UBOR(N,NP) = XSGBOR(N1)*UM
       VBOR(N,NP) = YSGBOR(N1)*UM
       WBOR(N,NP) = 0.D0
 50  CONTINUE
     DO 90 NP=4,NPLAN
       UBOR(N,NP) = -XSGBOR(N1)*UM*2
       VBOR(N,NP) = -YSGBOR(N1)*UM*2
       WBOR(N,NP) = 0.D0
 90  CONTINUE

     GOTO 60
!
!    *****
     ENDIF
!    *****
!
     N1=N
     N=KP1BOR(N)
     GOTO 30
!
 60  RETURN
     END SUBROUTINE Q3D
```

APPENDIX 5: The Lower Layer Flows

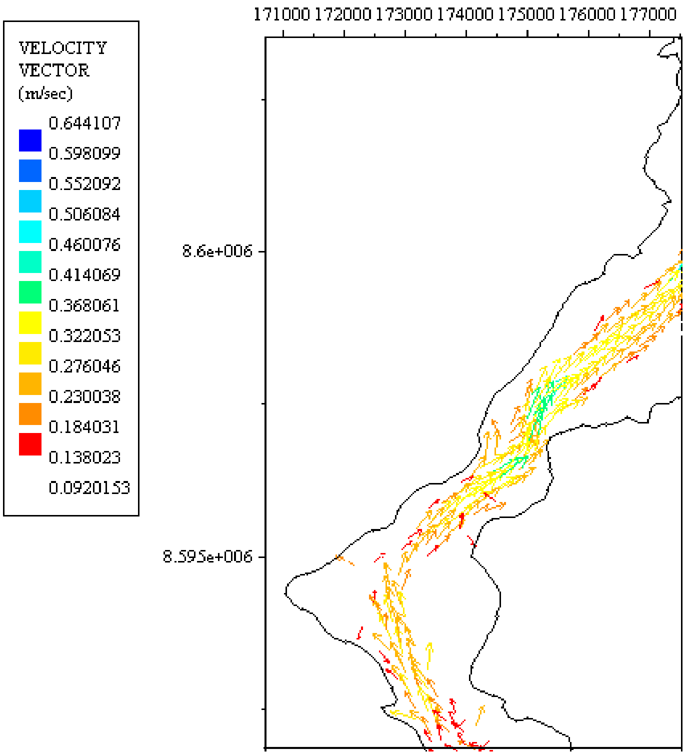

Fig. (A5.1): The velocity vectors of the lower layer passing through Sarıyer-Beykoz setion.

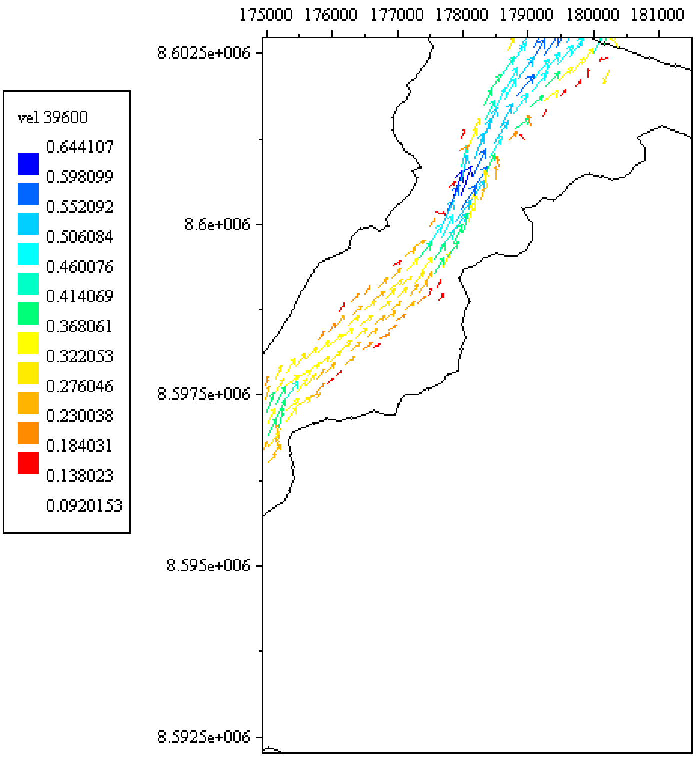

Fig. (A5.2): The velocity vectors of the lower layer entering the Black Sea exit.

APPENDIX 6: Vertical Cross-Section Along The Bosphorus Strait

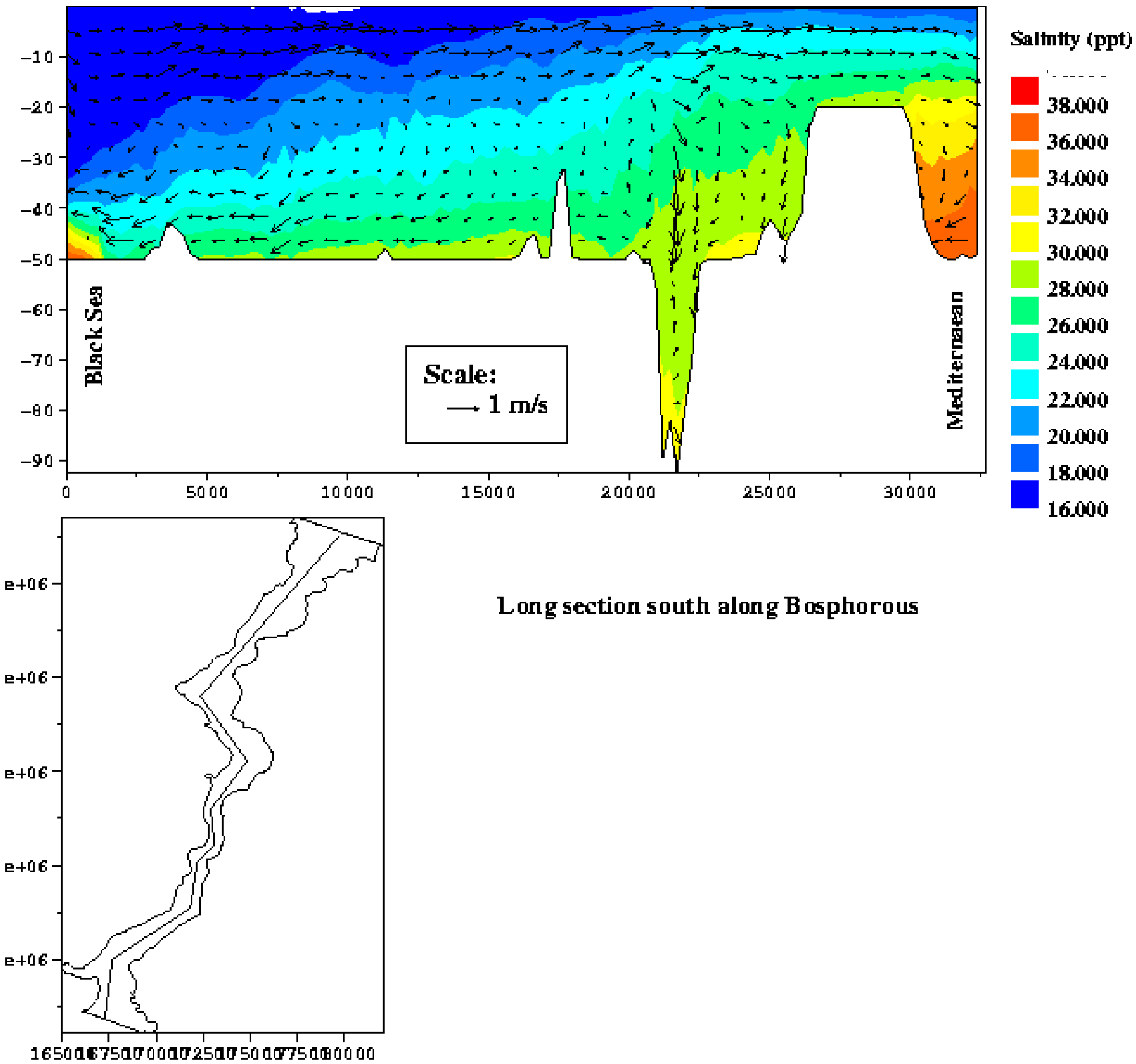

Fig. (A6.1): Vertical mixing along the Bosphorus Strait.

AUTHOR RESUME

Onur Akay was born in Izmir, Turkey in 1977. He had started to study at Izmir 60.Yıl Anatolian High School in 1990 and graduated from the science and mathematics department in 1996. He began to study civil engineering at Izmir Dokuz Eylül University in 1996 and graduated from the Engineering Faculty in 2000 by ranking first at his department. In the same year, he began to study at Istanbul Technical University Civil Engineering Faculty Hydraulic Master Programme. He has been working at Hydraulics Division as a research assistant since 2001.